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PV Reliability Operations and Maintenance (PVROM) Database Initiative: 2014 Progress Report

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PV Reliability Operations and Maintenance (PVROM) Database Initiative: 2014 Project Report

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ABSTRACT

To fill a major knowledge gap, Sandia National Laboratories (SNL) and the Electric Power Research Institute (EPRI) are jointly engaged in a multi-year research effort, supported by the Department of Energy's SunShot Program, to examine real-world photovoltaic (PV) plant reliability and performance. Findings and analyses, derived from field data documented in the PV Reliability Operations Maintenance (PVROM) database tool as well as from convened workshops and working group discussions, are intended to inform industry best practices around the optimal operations and maintenance (O&M) of solar PV assets. To improve upon and evolve existing solar PV O&M approaches, this report:

1. Provides perspective on the concept of PV "system" reliability and how it can inform plant design, operations, and maintenance decisions that produce better long-term outcomes;
2. Describes the PVROM data collection tool, its technical capabilities, and results generated from database content in 2014;
3. Presents ongoing research efforts that are meant to drive the solar industry toward PV O&M best practice protocols and standards; and
4. Reflects on future areas of inquiry that can help better forecast plant health (e.g., system component availability, component wear out, etc.) and associated lifecycle costs.

Ultimately, this report adds to the knowledge base of improving PV system O&M activities by discussing data collection and analysis techniques that can be used to better understand and enhance the reliability, availability, and performance of a photovoltaic system.

ACKNOWLEDGMENTS

EPRI and Sandia would like to acknowledge the U.S. DOE for both its support of the multi-year PVROM initiative as well as for its guidance in shaping associated research activities. The authors also thank the many data partners providing input to the PVROM framework along with participants in the Sandia Technical PV O&M Working Group. Their experience in this area is instrumental in being able to collect and compare O&M data to gain a more accurate understanding of O&M practices and develop improvements to those practices that result in greater reliability and lower installation and operational costs for solar PV systems. This work was funded by the U.S. Department of Energy's SunShot Initiative.

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In this report, Sandia National Laboratories (SNL) and the Electric Power Research Institute (EPRI) present research results for the second year of data collection and analysis associated with the Photovoltaic Reliability Operations and Maintenance (PVROM) database project. Research efforts span 36 MW_{dc} of distributed and utility-scale PV systems, and are focused on better understanding the nature and occurrence of events that impact the reliability, availability, and performance (i.e., overall production) of a PV system. Using the PVROM "process," a rigorous data collection, analysis and feedback mechanism can be developed and considered a best practice for PV plant owners and operators looking to go beyond simple data collection and immediate incident response. The process provides a means for analyzing the probabilistic nature of events to better inform owners and operators about when and where to allocate limited financial resources earmarked for O&M activities.

The PVROM project seeks to document hundreds of megawatts of PV systems, located across the U.S., to enable analysis of multiple system configurations, as well as a wide range of component types and operating environments. Unfortunately, a number of challenges, including the time commitment required of data partners along with the terms of their participation, have to date slowed progress toward this end. However, initial data partners are benefitting from rigorous event tracking and the learning and feedback associated with the PVROM process.

For example, the initiative's original data partner has submitted 26 months of event data from two tracking PV systems in the desert southwest, and has, in turn, been able to identify reliability improvements when compared against a predictive model for hydraulic cylinder seals used in the tracking system. Predictive model results have, meanwhile, been found to be close to actual events for tracker programmable logic controllers. (Participation by this data partner has finished due to a change in system ownership.) Another partner with multiple distributed PV systems in the desert southwest has entered data into the PVROM tool to learn about preventative maintenance tradeoffs and reliability and safety improvements. And a third data partner has finished entering Bill of Materials (BOMs), equating to over 468,000 line items, for the express purpose of tracking events at a high level of detail to develop specific sparing strategies. Currently, 4-6 months of event data are associated with these latter systems.

PVROM data can be utilized within another SNL-developed model, known as the PV Reliability Performance Model (PV-RPM), where failure distributions from partner data can be utilized for predictive scenario development and impacts to energy production. The PV-RPM model was built during the PVROM project's initial scoping effort and utilized to analyze data from a PV system operated by Tucson Electric Power and turn it into event distributions. Scoping efforts conducted in 2014 have revealed improvements that can be made to update the PV-RPM model for current PV system configurations, including financial metrics and updated event distributions. PVROM data from existing data partners is anticipated to be developed into new fault and failure distributions and used in 2015 in an updated PV-RPM model.

Separately, SNL and EPRI successfully hosted a second PV O&M workshop in 2014. In addition to industry expert presentations, SNL-EPRI presented results associated with PVROM that were well received. An outgrowth of the inaugural workshop in 2013, the SNL PV O&M working group is also currently working to develop a framework for better understanding PV system availability, which can be more accurately determined using metrics developed from PVROM analysis. These best practices are intended to help delineate "availability" from an equipment and performance perspective and seek to create clear definitions that can be incorporated into standardized O&M contract language.

NOMENCLATURE

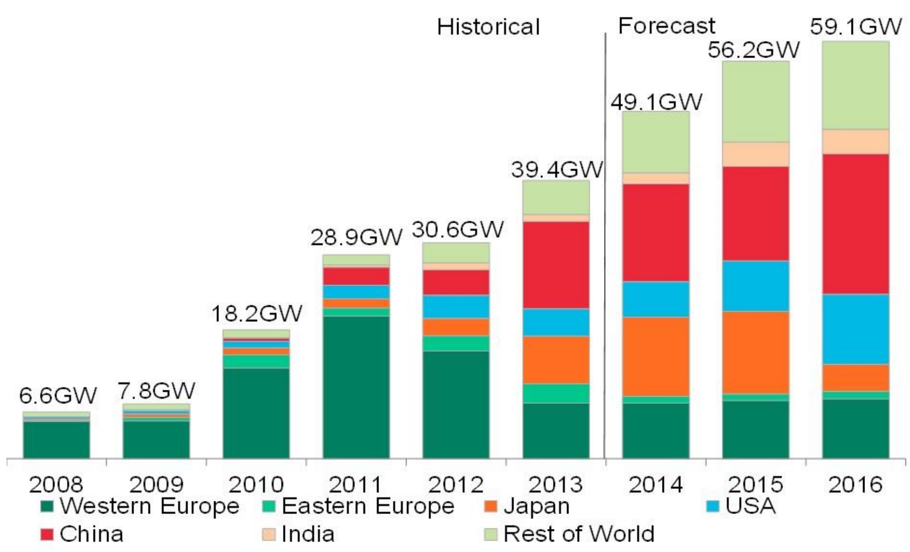
ac	alternating current
ASTM	American Society of Testing and Materials
BOM	bill of materials
BOS	balance of systems
CRADA	cooperative research and development agreement
dc	direct current
DAS	data acquisition system
DOE	Department of Energy
EPC	engineering procurement construction
EPRI	Electric Power Research Institute
FRACAS	failure reporting analysis corrective action system
GADS	Generating Availability Data System
ICOMP	Installation Commissioning Operation and Maintenance Process
IEC	International Electrotechnical Commission
IV	current-voltage
KPI	key performance indicator
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
MTBF	mean time between failure
MTBM	mean time between maintenance actions
MTTR	mean time to repair
MW	megawatt
MWh	megawatt-hour
NDA	non-disclosure agreement
NERC	North American Electric Reliability Corporation
NPV	net present value
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
OOS	out of service
O&M	operation & maintenance
PLC	programmable logic controller
PTC	PVUSA Test Conditions
PV	Photovoltaic
PVPMC	PV Performance Modeling Collaborative
PVROM	PV Reliability Operation Maintenance
PV-RPM	PV Reliability Performance Model
R&D	research and development
RBD	reliability block diagram
SCADA	supervisory control and data acquisition
SON	Sandia open network
STC	standard test conditions
SNL	Sandia National Laboratories
UAV	unmanned aerial vehicle

1. INTRODUCTION: OPTIMIZING PV SYSTEM O&M

1.1. Market Evolution & Increasing Significance of Lifecycle PV O&M

The pronounced worldwide growth of solar photovoltaics (PV) is beginning to steer greater industry attention towards operations and maintenance (O&M) planning and execution strategies. Solar's adoption trajectory, like other commercial technology maturation curves, has today reached a point in which assuring long-term plant reliability, through initial design and lifecycle O&M choices, is an increasingly important driver of the segment's overarching financial fitness and future market development prospects. Simply put, attracting ever-larger capital inflows to the sector continues to pivot on service and performance guarantees that are designed to reduce the investment risk profile of PV projects. As such, the relevance of O&M approaches that can efficiently mitigate or even preempt unplanned failure events—and perhaps raise plant performance and profitability expectations—should not be understated.

Unsurprisingly, then, the market for PV O&M service providers has, in fact, grown alongside PV's "hockey stick"-type expansion over the last decade. Cumulative global PV capacity reached 144 GW_{dc} at the end of 2013, and is expected to increase by nearly 50 GW_{dc} in 2014. Meanwhile, cumulative U.S. PV capacity is expected to grow by roughly 50% in 2014, approaching 21 GW_{dc}, and roughly quintupling tallies from just three years earlier.[1,2] Figure 1 portrays worldwide annual PV installations since 2008, and projected out to 2016. Looking ahead, forecasts issued by a sampling of industry analysts predict a further acceleration in PV adoption, particularly within the Asia, North America, and Latin America regions.



(source: Bloomberg New Energy Finance)

Figure 1. Global Annual PV additions, 2008-16E

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[1] Solar Market Comes of Age in 2013," SEPA Utility Solar Market Snapshot, June 2014: http://www.solarelectricpower.org/media/194339/Solar-Market-Snapshot-ver8-2-.pdf

[2] According to the Solar Electric Power Association (SEPA), the total number of U.S. grid-connected distributed PV systems rose to 475,000 in 2013, up from just 50,000 in 2009.

PV O&M companies have similarly exploded in number, offering a variety of segmented services packages across a range of price points, to monitor and maintain plant health. The addressable PV O&M market in the U.S., for example, is expected to grow from approximately 7 GW as of late 2013 to just over 20 GW by the end of 2014 (GTM Research / SoliChamba Consulting 2013). Of this market, the majority of O&M servicing is likely to be targeted at commercial- and utility-scale plants that require greater supervision (versus residential rooftop installations). And while efforts are likely to be localized in particularly active state markets such as California, Arizona, New Jersey, North Carolina, and Massachusetts, they are also expected to geographically expand in tandem with the resource's greater development. The global installed capacity of megawatt-scale PV plants is, meanwhile, expected to grow by 70% in 2014, from 26.8 GW in January to an estimated 45.8 GW by the end of the year (GTM Research / SoliChamba Consulting, 2014).

Status quo O&M approaches employ reactive, preventative, and conditional-based measures that map to the value that plant owners assign to system upkeep. They are often driven by the O&M budget that is available to the Engineering Procurement Construction (EPC) or O&M provider, as well as service quality expectations. These approaches have demonstrated differing levels of cost-benefit for a diversity of installed PV systems located in different environments and endowed with different designs. However, their make-up and implementation has typically not been considered as part of a comprehensive O&M strategy that coordinates, from the beginning, with a PV system's design, development, and lifecycle operation. Historically, O&M has often been considered an added cost by plant owners and financiers, and has consequently been streamlined to balance profit motives with basic asset management objectives. Going forward, O&M budgets may require greater flexibility to respond to new system designs as well as the needs of the O&M provider, who will be working to ensure optimal operation of aging systems.

There is merit to more comprehensively incorporating O&M strategy into PV system planning, design, and asset management activities. More systematic adoption of O&M best practices into evolutionary phases of PV plant development has the potential to better recognize cause and effect relationships that can, in turn, help to increase product quality and long-term reliability, while reducing costs—all increasingly important outcomes given both the global proliferation of PV plants as well as expectations that they will be operational over 20-30+ year time scales. As PV assets change hands over the course of their lifetimes, well documented O&M activities will, furthermore, be required to ensure that the best financial outcomes are consistently realized for both asset sellers and buyers.

The industry is, in fact, currently formulating new standards and best practices that aim to more fundamentally consider O&M when making PV plant construction and contractual business decisions. Workshops and conferences are also increasingly emerging to promote greater knowledge share around O&M innovations, business apporoaches, and their associated costs and benefits. (The rising number of O&M events is perhaps also an indication of a widening sentiment that solar O&M represents a next big area of business opportunity).

For example, Sandia National Laboratories (SNL) is leading a multi-stakeholder PV O&M Working Group effort to better understand the existing gaps in O&M best practices and improve upon the "availabilty" definition used for describing the equipment and performance of a PV system. These activities are being coordinated along with those undertaken by the SunSpec Alliance and the National Renewable Energy Laboratory (NREL) to develop an O&M cost modeling framework for better distinguishing the interrelationship between upfront O&M costs and the probabilistic nature of how certain events impact maintenance actions, response times and costs. And finally, the American Society of Testing and Materials (ASTM) International task group (WK43549) is working to provide standards for foundational metrics and processes to guide the Installation, Commissioning Operation and Maintenance Process (ICOMP). ASTM, in concert with contributing stakeholders, is working to define the integrated process and approved best practices necessary for consistently delivering reliable PV lifecycle performance.

These activities are all ultimately being undertaken to bolster PV performance reliability as well as to increase the surety of PV system financials over the life of the PV installation.

1.1.1. Effort to Improve PV System Reliability: PVROM

As part of the effort to address a knowledge gap in the O&M of medium to large solar photovoltaic systems or plants (>100 kW), SNL and the Electric Power Research Institute (EPRI) have co-developed the PV Reliability Operations and Maintenance (PVROM) database tool to conduct empirical performance and reliability analysis of real world field data. Explored initially in 2007, and formally launched in 2013, the tool is intended to house a growing data sample that is incrementally shared by industry partners. In addition to PV plant design information—which establishes a baseline understanding of a system's equipment makeup and layout—partners are expected to submit PV plant performance and availability metrics as well as document planned and unplanned incidents (e.g., reduced output, outages, etc.). These details can then be translated into vital numerical data for a diversity of geographically dispersed plants, and used to conduct nuanced trend analysis and statistical modeling.

The underlying supposition of the PVROM research effort is that accurate plant data reporting can help both recognize and characterize the events that affect PV system production—such as component and system failures—and better understand their associated lifecycle impacts. In addition, optimal maintenance and mitigation approaches can be discerned, such as spare parts needs as well as nuisance alarms handling, and plant design best practices determined. The initiative furthermore offers an outlet for exploring a range of analytic techniques that can unearth valuable performance-related insights.

Note: Throughout this report, PVROM is referred to as a tool, database, and project. Overall, the different aspects of PVROM contribute to the "process," a best practice where data is collected, analyzed, and reliability improvements are made.

1.2. Project Team

The multi-year PVROM project is led by SNL and EPRI, formalized through a Cooperative Research and Development Agreement (CRADA) on November 19, 2013. The CRADA establishes the joint goals of the partnership, which are to improve PV system O&M through reliability research and analysis. Specifically, both SNL and EPRI "will collaborate and reach out to the community to cooperate, collaborate and facilitate establishment and access to photovoltaic (PV) plant data for use in the Photovoltaic Reliability Operations and Maintenance (PVROM) database…"

Project partners, including utilities and O&M companies that operate primarily in the southwestern U.S., have been recruited to participate in PVROM effort for roughly three years. The PVROM initiative relies on active participation and event data entry to accurately capture PV system fault and failure episodes, as well as subsequent strategies employed to determine root causes of failure events and ensure high equipment availability. The time range, quality, and amount of data available for analysis is primarily related to how much time the data provider has to participate in the effort. PVROM partners are the principal sources of the PV plant field data stored within the database tool. In exchange for inputting their plant information into PVROM, industry partners gain access to the database's repository of solar plant data as well as to its functionality in order to benchmark system performance and recognize cost-benefit tradeoffs of value chain modifications.

SNL and EPRI have co-developed the PVROM database and standardized tool. In addition, the two organizations are jointly:

- Overseeing the operation and maintenance of the database,
- Providing database access usage training to industry partners,
- Performing research and data analysis of plant data housed in the database via existing PVROM algorithms,
- Developing further technical and administrative functionality embedded in PVROM (e.g., new algorithms, additional database parameters to collect specific kinds of PV O&M information, etc.), and
- Supplying cyber security capabilities for the PVROM database.

Following are brief descriptions of each of the core contributors to the PVROM research effort.

Sandia National Laboratories

Sandia National Laboratories, managed and operated by the Sandia Corporation (a wholly owned subsidiary of Lockheed Martin Corporation), is comprised of two United States Department of Energy research and development national laboratories located in Albuquerque, NM and Livermore, CA. Although Sandia's primary mission is national security, the Lab's R&D activities also extend to alternative energy technologies, such as solar photovoltaics.

Specific to solar, Sandia's work is focused on developing cost-effective, reliable PV energy systems and accelerating the integration of PV technology. The lab's PV department provides the technical lead for systems integration and balance-of-systems manufacturing technologies as well as technical support to the U.S. DOE in deployment and validation of PV systems for federal agencies, utilities, and other institutional users. Sandia assists industry and users by providing technical assistance, accurate performance measurements, component development and improvement, and system evaluation. A major thrust of the department is to evaluate and improve the performance, reliability, and cost effectiveness of systems and balance-of-systems components.

Sandia brings the technical expertise of standardized data collection and reliability analysis to the cooperative PVROM project. It is applying this expertise toward the further refinement of the PVROM database and collection tool, and to developing standardized methods for analyzing O&M data for predicting PV systems lifetime.

For more information: http://www.sandia.gov.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), established in 1972, conducts research, development and demonstration (RD&D) relating to a range of generation, delivery, and use of electricity issues. An independent, nonprofit organization, the institute brings together scientists and engineers as well as experts from academia and industry to address challenges germane to the electricity segment. Solar-related research includes field and laboratory technology testing, grid integration modeling, O&M approaches, and distributed generation business models.

Worldwide membership exceeds 1,000 organizations, predominately composed of electric utilities that collectively represent ~90% of the electricity generated in the United States and that reside in over 30 countries internationally.

For the PVROM initiative, EPRI is assisting with the further technical development of the PVROM database in order to inform, validate, and update the existing PVROM data collection tool. It is also performing outreach to third party PV system owners with the aim of contractually incorporating greater amounts of PV reliability and availability field data into the database. Additionally, the Institute is, in collaboration with Sandia, performing analysis of empirical data derived from the PVROM database.

For more information: http://www.epri.com.

PVROM Partners

PVROM Partners—utilities, owner/operators, third-party O&M providers, and others—are responsible for initially entering and periodically updating field data information about their respective PV plants into the PVROM database. The value of the PVROM tool is directly linked to the number and size of industry partners that affiliate with the research effort. As of this writing, four partners have agreed to participate in the initiative, representing approximately 36 MW of PV systems spanning 38 PV system sites.

Among the multiple benefits that PVROM Partners receive via project participation are:

- Data anonymity enforced by a Non-Disclosure Agreement.
- Full database access to individual partner-entered data.

- Access to aggregated database content entered by other partners, normalized for use (contingent upon database sample size).
    - Analysis of aggregated data is intended to provide partners with a way to benchmark their plant performance/reliability results with a larger sample, while also maintaining a level of anonymity.
- Increased recognition and understanding of PV availability versus reliability (and associated O&M options based on output).
- Better understanding of system costs and cost-benefit of multiple O&M approaches based on various factors.
- Better understanding of the risk of possible future PV plant states (e.g., ID insurance products).

1.3. Brief History of the PVROM Project

1.3.1. Objectives

The primary objectives of the PVROM initiative encompass the data gathering and empirical analysis of PV reliability and performance field data. Although PV system installations have spiked over the last several years—approaching nearly 21 GW_{dc} of capacity in the United States alone—access to PV field data information has, to date, been limited given its proprietary nature. Most plant owners, investors, and third-party O&M providers have, by and large, been unwilling or unable to share solar system data due to contractual obligations and/or competitive concerns. As a result, industry-wide knowledge concerning optimal plant design, operation, and upkeep, as well as lifecycle economic outcomes, is lacking.

The PVROM effort, founded on industry collaboration along with technical R&D, is intended to help remedy this situation. In co-developing the PVROM database and a standardized data collection tool, SNL and EPRI have devised a method for collecting, analyzing, and assessing events and failures that occur in medium to large (>100 kW) PV systems. As of late-2014, the two organizations are no longer engaged in active recruitment of industry partners, and have since more exclusively transitioned to wide-ranging analysis and data exchange.

Specific project objectives, further elaborated upon later in this report, include:

- Recruitment of industry partners to input their PV plant data into the PVROM database,
- Training and consultation with industry partners to assist with their data entry and retrieval,
- Data collection and empirical analysis of plant reliability, availability, events, failures, and other metrics,
- Publication of reports on trends observed from the PVROM data as well as data collection methods, and
- Identification of optimal O&M practices that can be applied toward the development of standardized O&M protocols for broad industry use.

1.3.2. Outreach and Partnerships

In 2007, five years of failure and repair data was obtained through Tucson Electric Power from the Springerville Generating Station PV system located in eastern Arizona. The Springerville plant effectively represented the first implementation of the PVROM process. At the time, this facility was one of the largest PV generating plants in the world at 4.6 MW_{dc}. The data collected from Springerville was analyzed and led to the creation of the first reliability and availability models based on actual PV system field data (The Springerville data was incorporated into SNL's Photovoltaic Reliability Performance Model, PV-RPM, described in Section 3.2.1).

In anticipation of additional O&M data partners, project stakeholders investigated the use of a more robust tool to facilitate the gathering and analysis of PV system reliability and maintainability experiences. After an evaluation of various off-the-shelf software packages, the XFRACAS™ software from ReliaSoft was selected as the data entry, retention, and analysis tool for the PVROM process (Collins et al., 2009). The Springerville data provided by Tucson Electric Power was soon after entered into the database for a proof-of-concept of the end-to-end PVROM process (Collins et al., 2010).

Next, both SNL and EPRI developed a targeted list of over 100 potential contacts, consisting of fully integrated PV providers, utilities, EPCs, O&M providers, banks, developers, independent engineers, and Original Equipment Manufacturers (OEMs) including inverter and module companies. Outreach materials comprised a two-page summary of the project's background as well as stakeholder roles, responsibilities, and benefits; a frequently asked questions document was also distributed that conveyed a range of details, including data and date entry requirements, confidentiality issues, and anticipated research results.

In addition to determining their availability to input data, potential partners were also asked to consider signing a three-way non-disclosure agreement (NDA) between the data partner, SNL, and EPRI. The intent of the NDA was to agree on each partner's level of disclosure. Many in the industry would like to see specific component and manufacturer fault and failure information as a result of the PVROM effort, though some partners would rather keep that information generic and not specifically name OEMs or provide power plant-specific details. As the goal of this work is to collectively understand PV owner and operators response to O&M activities and analyze a fleet of PV system information, SNL and EPRI were able to enter into agreements that address many of the participants' concerns regarding disclosure. It would likely be easier to recruit additional partners if the adherence to an NDA was not required or necessary, however the industry is still maturing and through this process it was discovered that many owners and operators would rather keep that data for competitive advantages at this point in time.

1.4. Phases, Tasks and Schedule

PVROM has initially been funded to run over 36 months, beginning in fiscal year 2013, although this timeline is subject to change. Table 1 illustrates the initiative's research plan. Partner recruitment has been an ongoing activity since the initiative's start. However, active outreach has, since Q3 2014, been curtailed as the project dovetails more exclusively into data collection and analysis. As of this writing, four partners have signed up with three actively participating, although their full participation has been slowed by a number of unforeseen challenges (see below).

This status report, as well as another scheduled for publication in 2015, represent the key deliverables of the project. They are intended to relate notable analytical findings derived from database content as well as convey other research activities that aim to leverage PV O&M best practices to improve PV plant reliability and lifecycle performance.

In concert with the PVROM tool's development and use, project stakeholders are facilitating dialog and knowledge sharing among O&M practitioners to help advance the sector's market relevance and recognized value. To this end, EPRI and SNL have convened separate PV reliability and O&M workshops in 2013 and 2014. Each has explored a range of topics including current and conceptual O&M approaches for improving plant performance and reducing the levelized cost of solar electricity, advances in component reliability, and data-driven strategies for performing economically efficient system upkeep. A future meeting is tentatively scheduled for 2015.

In addition, SNL and EPRI staff have been heavily engaged in O&M working group efforts to define O&M knowledge gaps and needs assessment, document current industry practices, and identify/suggest protocols that can be implemented into codified standards. These activities are being coordinated with ASTM International's WK43549 ICOMP working group to aid in the development of standards by broader consensus bodies in the 2015-2016 time frame.

Table 1. Project Research Plan

	2013				***2014***				***2015***			
	Q1	***Q2***	***Q3***	***Q4***	***Q1***	***Q2***	***Q3***	***Q4***	***Q1***	***Q2***	***Q3***	***Q4***
Phase I												
O&M Workshop		■										
Partner Recruitment			■	■								
Data Inputs			■	■	■							
Working Groups/Practices Dev.			■	■								
PVROM Report				■	■							
Phase II												
O&M Workshop						■						
Partner Recruitment					■	■	■	■				
Data Inputs					■	■	■	■				
Best Practices/Working Groups					■	■	■	■				
Initial O&M Benchmark Report								■				
Initial Practices/Draft Standards								■				
Phase III												
O&M Workshop										■		
Data Input/Maintenance									■	■	■	■
Standards Development									■	■	■	■
Standards Completed/Turnover												■
O&M Benchmark Data Report												■

1.4.1. Project Challenges

A number of unforeseen issues emerged over the last year that has slowed data collection and analysis work. For example, PV system ownership changes and staff turnover at partner organizations have either impeded or delayed PV plant data share. Meanwhile, the somewhat labor-intensive nature of Bill of Material (BOM) creation and time commitment necessary to establish user accounts on SNL servers (where the PVROM database is hosted) and complete requisite training have also presented partner challenges. Also, long stretches of time have passed in which no events have occurred at the plants being monitored, hinting at the need to evaluate performance reliability over longer time horizons.

An overarching result of these unanticipated events has been a more limited data sample size than expected. These lessons learned have, however, been documented and solutions subsequently presented to help pave the way for a greater, unobstructed flow of information into the database. Stakeholders remain committed to leveraging the full value of PVROM. Moreover, despite these difficulties, the level of data collection achieved in 2014 has been adequate to illustrate a number of worthwhile insights.

2. PVROM DATABASE TOOL: PROCESS AND CAPABILITIES

PVROM can best be described as a process where high quality data is collected and analyzed using reliability engineering principles and statistical methods. It is primarily composed of two pieces:

1. A database that allows for proper serialization of PV plant components, recognizing the parent-child relationship of components connected in series and/or in parallel, and

2. A Failure Reporting Analysis Corrective Action System (FRACAS) that emphasizes continual improvements through a feedback process that aims to "close the loop," thus reducing the likelihood of recurring failures.

The latter piece is accomplished through rigorous tracking, data storage, and analysis of the many components and sub-components that comprise an entire PV system.

Fragmentation of the PV industry poses a challenge to get broad data sets that are representative of the entire PV segment. As a result, assembling such a data set requires involved partner collaboration. From the PVROM partners' perspective, participation for the benefit of the industry must be balanced with the need to safeguard competitive advantages in the data—though this could change as the industry matures. Therefore, at this point in time, security and trust is especially important to the success of PVROM. The PVROM database resides on an SNL server and is accessed through the SNL open network (SON). Access restrictions ensure that only source users (industry partners) can access the database. SNL administers security protocols and XFRACAS™ source permissions ensure that individual source users can access only their own data.

This section presents the framework for PVROM along with conceptual examples of the type of analysis that can be performed. Preliminary results derived from partner data are discussed in Section 3.

2.1. The FRACAS Approach

A FRACAS approach is used heavily in manufacturing, including aerospace and defense, where complex systems need methods for tracking events and maintaining a high degree of reliability (DOD, 1980; 1985). According to a survey conducted by the Reliability Analysis Center, FRACAS was rated as the number one reliability activity in terms of importance. (Criscimagna, 1995) As the PV industry matures, use of this approach aims to help reduce system downtime, as well as improve costs and overall PV system performance. In short, PVROM is meant to facilitate the transition from anecdotal evidence to informed results.

The FRACAS approach is not new to the solar industry. PV inverter OEMs utilize a FRACAS approach, as evidenced from a presentation by PV Powered (now Advanced Energy) made in 2009. Their focus was to educate the industry and their customers about their predictive reliability modeling, as well as results from fielded studies.[3] A presentation in 2011 by Dow and ReliaSoft, meanwhile, highlighted use of the FRACAS approach to product development and improvement for the Dow Powerhouse Shingle product.[4]

SNL published a comprehensive report on the use of a FRACAS approach for developing a process for collecting and analyzing PV system reliability data (Hamman, 2014). This approach, devised specifically for the PVROM process, utilizes the XFRACAS™ tool from ReliaSoft to store PV system configuration and reliability data. The web-based, closed-loop, incident (failure) reporting, analysis, and corrective action system software package is specifically designed for the acquisition, management, and analysis of quality and reliability data from multiple sources.[5] The ability to export PV system times-to-failure and times-to-suspension for ready analysis by other ReliaSoft analysis tools (Weibull++™ and RGA™) was a primary consideration in choosing XFRACAS™ as a reliability data collection tool for PVROM.

The tool enables:

- Reporting of reliability-related issues for PV systems and components in the field,
- Specification of failure analysis details,
- Tracking of failure analysis and mitigation actions associated with resolving identified field problems,
- Reporting of installation details when a PV system is installed/commissioned,
- Review of PV system configurations Bills of Material (BOM),
- Search of customer support, incident, problem resolution report, action, failure analysis, and system configuration records based on specified criteria,
- Data export to other tools beyond XFRACAS™ for additional analyses.

One of the benefits of the tool is that, in addition to faults and failures, preventative maintenance, cost and performance can be tracked. PV system equipment availability can also be calculated, which is an important contractual term that is often seen alongside performance guarantees and performance ratios for those performing O&M activities.[6]

2.2. PVROM Inputs and Data Requirements

This section describes the types of data collected by PVROM, including events, faults, failures, plant performance and costs. It also outlines the statistical insights that can be gleaned from data inputs and presented in the form of graphs, charts, and tables. Derived insights are designed to help current data partners, or other users of the FRACAS "framework," understand the reliability, performance, and cost impacts of their O&M decision making. Reports to data partners are structured around this section's material to provide a consistent template. It is

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[3] http://av.conferencearchives.com/pdfs/091001/58.1119.pdf

[4] http://www1.eere.energy.gov/solar/pdfs/pvmrw2011_04_plen_guo.pdf

[5] The FRACAS (Failure Reporting, Analysis, and Correction Action System) in XFRACAS™ is a general term for a database used in quality, reliability, or maintainability engineering applications that tracks problem in a system. Ultimately, these problems can be corrected through root-cause analysis using the recorded data as well as generate reliability/maintainability statistics for prediction in future analyses.

[6] PV performance guarantee is the amount of plant generation that is guaranteed to be produced within defined periods of time, while PV performance ratio is the ratio between actual plant yield (i.e. annual production of electricity delivered at AC) and the target plant yield.

anticipated that having access to this summary data will result in better “learning” over time, and subsequently greater PV system uptime. As stated above, it is important to note that the rest of this section represents results “examples.” Real results from data partners are presented in Chapter 3.

Industry partners are responsible for inputting PV plant design information into the PVROM database to establish a baseline understanding of a system’s equipment makeup and layout. Subsequently, they are expected to capture planned and unplanned incidents and events and record them into the PVROM database. This is done through a process of documentation in incident reports that each reflect single plant outage events. The detailed information in the incident reports allows for vital numerical data to be generated—such as times to failure and time to restoration per component per outage event—and lays the foundation for more nuanced trend analysis and statistical modeling. Most importantly using a holistic approach and system-wide view of issues allows systems owners to better understand single root-causes underlying multiple outages and provides for targeted improvement that grows reliability. What follows is a brief explanation of primary PVROM data inputs, outputs, as well as operational and analytical capabilities.

The amount and quality of the reliability data available for analysis will have a large impact on the type of analysis conducted as well as the degree of insight unearthed. For example, ascertaining the overall O&M costs associated with a level of activity—especially when the goal is to reduce cost uncertainty through the identification of an optimal O&M schedule or from having spare parts on hand—is a data intensive undertaking.

The tables in the sub-sections below illustrate the type of data that SNL needs for input into the FRACAS portion of the PVROM framework.[7] Much of this data can also be used within another SNL developed tool, PV-RPM, described in Section 3.2.1, which goes beyond traditional reliability analysis by combining it with system performance models based on SNL’s PV Array Performance Model (King et al., 2004). Combining reliability statistics with a PV performance model provides more accurate predictions of overall PV system performance due to a more realistic representation of how PV systems actually perform in the field. The largest roadblock to utilizing reliability metrics in a PV performance model, however, is that data is not generally available as it can only be developed through a process where PV systems are analyzed over time, or component manufacturers are willing to provide fault and failure distributions of their products through an analysis of data they collect during maintenance events, e.g. warranty repair or replacement.

Base installation detail, reliability metrics, PV system performance, and O&M related costs associated with downtime events make up the four main areas required for comprehensive analysis via PVROM. If this level of detail is not collected, certain failure modes, trends, and insights may be missed and lead to decreased PV plant performance and lower availability, or conversely, “unavailability,” which is the fraction of a given operating period in which a system component is not performing its intended services within the design specification.

[7] SNL currently uses XFRACS™ as the enhanced database for capturing reliability data. It allows for integration with Reliasoft’s multiple statistical analysis tools, including Weibull++, ALTA, RGA, and BlockSim. Other platforms could be utilized to collect reliability data and perform similar type analysis.

2.2.1. Base Installation Detail and Bill of Materials (BOM)

An important task is setting up the BOMs into a format that recognizes the dependency of components in the system, similar to how a reliability block diagram (RBD) sets up the parallel and series relationships in a system. Readers are encouraged to see the report by Hamman (2014) for more detail on how to set up a FRACAS for large PV systems using the XFRACAS™ software tool.[8] An example of the type of information that can be used to set up the BOM is presented in Table 2. The more detail that can be provided, the better the statistical results.

BOMs form a sort of taxonomy, derived from the physical construction of the PV system, by which to assign events. They are created to capture the inventory of a system down to a desired level. As such, they organize a PV system in a hierarchical manner and can track what system components may be subassemblies of other components.[9]

Table 2. Base Installation Detail

Description of Data Need	Notes
PV System Owner	Ownership structure over time is requested if PV system has changed ownership.
PV System Installer	The original EPC or installer. Workmanship warranties pass down for 1 or 2 years from the installer.
PV System Location	Latitude, longitude (of corners if PV system is large). State, address, elevation.
As-built drawing	Often the draft plans differ from the as-built. Drawings over time are necessary if system has changed configuration.
Commissioning Date	The date of commissioning – Initial, and subsequent, if any. Also, what standards or best practices were followed in the commissioning process.
In Service Date	The date the PV system was connected to the grid.
O&M Contract	These contracts typically have definitions and procedures that must be followed. Availability and Performance Guarantees are spelled out in these documents.
dc Nameplate Capacity	Total system "nameplate" capacity in dc kW or MW.
Array Size	Both dc and ac power and energy ratings in STC/PTC, including any de-rating information, especially if there are high dc to ac ratios.
Array Operating Voltage	This will help bracket any excursions away from the operating voltage window that may cause damage if circuit breakers or inverter controls are not functioning properly.
Configuration/Application	Mounting description – ground or roof fixed, tracking, etc.
Utility/Grid Details	Information on transformers, switchgears, regulatory requirements (NERC, if required).
BOS components	Wiring, junction boxes, dc optimizers, home runs, etc.
Component Bill-of-Materials	A spreadsheet or database in a specified format that lists the all the system components to be tracked for reliability and maintainability data. This data would include component model numbers, description, quantities, manufacture, and serial number for individual components. Components should be traceable to the system as-built drawings.

Before field incident data can be entered into the XFRACAS™ database it is necessary to construct an appropriate PV installation BOM. The first step in creating a BOM for a PV

[8] http://energy.sandia.gov/wp/wp-content/gallery/uploads/SAND2014-2914-XFRACAS-as-PVROM-Tool.pdf
[9] System components may include hardware parts and software components.

installation (using XFRACAS™ in our case) is to obtain or create a detailed configuration of the installation, such as an electrical one-line diagram. A PV installation will typically consist of power transformers, ac and dc disconnect switches, inverters, dc optimizers, PV modules, data acquisition systems and various ac and dc system connections (e.g., cables, fuses, diodes, etc.). PV installation components can generally be grouped into one or more power blocks, where a power block consists of the collection of components associated with, for example, an inverter. It is recommended that a BOM be created for each unique system power block or geographic site.

BOM data can be directly entered into XFRACAS™, but usually a BOM template is filled out by the system owner in a Microsoft Excel template as manual entry is time consuming when compared to the automated uploading of a completed template. Table 3 shows an excerpt of a completed template as taken from Hamman (2014). Each component will have a part number that will be shared with many other components, and each individual component will have a unique serial number establishing it as a unique member of the population of components in the BOM. Commissioning dates must also be provided in the Build Date column for all BOM entries as this establishes the "birth date" of system components. Metrics such as time-to-failure (or time-between failure in the case of repairable components) is calculated based on a component's commissioning date.

Table 3. Base Installation Detail

Level	Part Number	Part Description	Part Version	Serial Number
1	SGSSS	SGS Solar System Power Block		SGS-1
2	TXL	480V/34.5kV Transformer		SCL-2
2	TXS	208V/480V Transformer		TXS-1
2	ADS	AC Disconnect Switch		ADS-1
2	DDS	DC Disconnect Switch		DDS-1
2	ECON	Array Electrical Connections		ECON-1
2	INV	Inverter		INV-1
2	LIGHT	Lightning Event		L-1
2	MOD	PV Module		M-U1-1
2	MOD	PV Module		M-U1-2
2	MOD	PV Module		M-U1-3

The "Level" column in Table 3 connects components in what is called a "parent-child" relationship. XFRACAS™ views a child component, specified as a Level, a single increment greater than its parent, as related to the parent in a special way. Specifically, if the parent is replaced during the course of maintenance activities then it is assumed that all the children of that parent component are replaced. This would be implemented when you have components within components, for example a controller board within an inverter or perhaps a fuse within a disconnect switch. New serial numbers would be entered in for all the new components parent and child and its commissioning date would be based on the time of replacement. The system is also flexible enough to go beyond hardware components and also track items such as software. Incidents written against such an item could include faults discovered on the system that required either a reset, patching, or upgrade to the software.

Upon completion of the BOM template, the XFRACAS™ administration tool is used to upload the form directly into PVROM. The system is now ready to record incidents, a process described in the next section.

2.2.2. Reliability Metrics

Incidents, the primary inputs to the PVROM database, are defined as failures, faults, or trips of PV plant systems or components that lead to outages. These outages can occur when a system is operative and performing as designed, or conversely when a system is malfunctioning. Innocuous incidents such as nuisance trips can be quickly addressed without major effort, while failures causing loss of component function can necessitate greater repair or replacement actions. Preventative maintenance is also tracked so as to measure its impact on system performance and, with enough data captured, its impact on long term component reliability. Table 4 lists the various pieces of information that are typically included in an incident report.

Table 4. Reliability Metrics

Description of Data Need	Notes
Incident Title	Brief statement that summarizes the description of the incident.
Incident Description	A more detailed description of the incident. This would have information regarding how the failure manifested or the details of what prompted a planned event. This would include information regarding any abnormal conditions either related to disturbances of the grid or environmental conditions (weather).
Occurrence Date	The date and time that the incident occurred.
Creation Date	The date and time that the incident was created in the PVROM database.
Warranty Repair	Is the item currently covered by an active warranty?
Service Response Date	The date and time that maintenance personnel responded to the incident.
Incident Status	The incident can be “open,” “closed,” or “under review.”
Service Response Date	The date and time that maintenance personnel responded to the incident.
System Status	Current operational status of the system affected by the incident. Available, unavailable, degraded, etc.
Incident Report Type	Is the incident documenting a planned or unplanned maintenance event?
Incident Category	A high-level description of the failure or maintenance action. Examples include hardware failure, environmental induced failure, planned maintenance, software upgrade, etc.
Restored to Duty	The data and time that the component associated with the incident was brought back to an operational state in the system. This assumes that all repairs and testing has been completed.

Description of Data Need	Notes
Active repair duration	The total time, in hours, for the active "hands on" repair time of components associated with the incident. This does not include logistical related activities such as mobilization of maintenance crews or acquisition of spare parts.
Incident Resolution	A description of what action was taken to affect restoration of the component and the system.
Initiating Event	A description of factors that caused the incident to occur or be written. Includes a description of the known root cause.
System Hours	The amount of system hours accumulated on the system at the time of the incident occurrence.
Operating Time Prior to Failure	Time between failures.
Severity to System	This can be based on what the operator determines necessary to track, in terms of potential cost to cure and downtime.
System Down Event	The cause of the event impacting equipment availability.
Warranty Repair	If component is repaired/replaced under warranty.
ac kWh Loss	Loss estimated or tracked as part of nearest neighbor (function of time) or through daily performance model or forecast tracking.
Tables of Reliability Data	Historic data if tracked prior to using PVROM.
Failure Modes	Any and all known or anticipated failure modes, either obtained from OEM or knowledge of other system failure modes.

Incidents of all types are intended to be logged into the PVROM database along with additional information that can assist in the analysis of the outage's cause(s). Failures leading to outages as well as deliberate de-energizing of systems or equipment for purposes such as repair or preventative maintenance are included as incidents that are being recorded in the database. Figure 2 provides a screenshot depicting the look and feel of an XFRACAS™ incident data report.

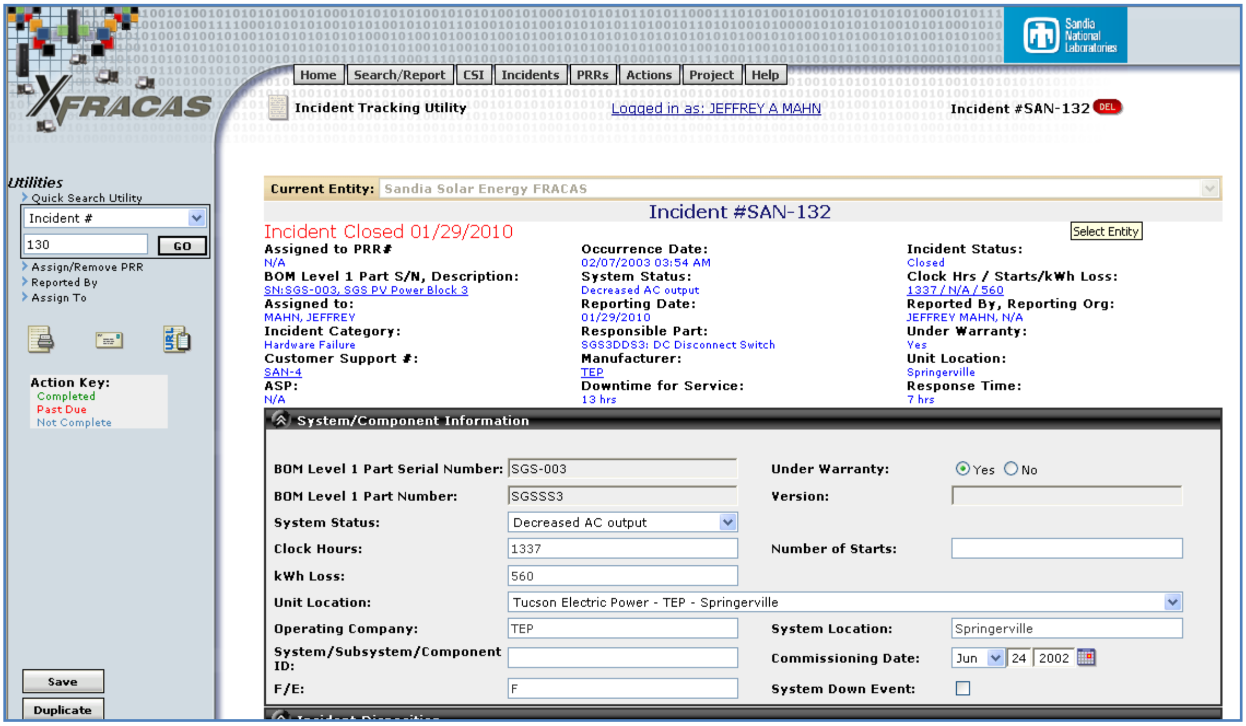

Figure 2. XFRACAS™ Incident Report Example

As previously discussed, the other major inputs to the PVROM database are identified as *incidents*, which represent maintainability data, such as outages, maintenance actions, and power losses. Outages caused by either failures of system components or external disturbances on the system itself are recorded as incidents. Some of the categories that are being used in PVROM are shown in Table 5.

Meanwhile, the way that an issue is documented in PVROM is called an *Incident Report***,** which captures the following information regarding an outage event:

- Date of occurrence,
- Description of the problem,
- Affected component and location within the system by serial number,
- Corrective action taken to restore availability of the component,
- Repair and restoration time of the component, and
- Estimated energy loss from the system caused by the component outage.

Table 5. Range of Incident Categories Recorded into PVROM

Specified Incident Categorizations

Incident Category	Definition
Hardware failure	Any hardware component of the system in the BOM that has failed or stopped working (includes operational suspensions resulting from degraded electrical connections)
Software problem	A fault or failure due to a software error, glitch or incompatibility; the root cause is not a hardware failure • Example: inverter failure due to incorrect limits in the code
Hardware upgrade required to operate	Hardware upgrade requirement based on changes in the electrical code or to utility requirement • Example: changes to anti-islanding policy requiring new inverters
Software upgrade required to operate	Software upgrade requirement based on changes in the electrical code or to utility requirement • Example: changes to anti-islanding policy
Equipment installation problem	System downtime due to incorrect installation • Example: incorrect grounding of modules or inverters, misaligned trackers
Grid-induced failure/suspension	Any system upset condition caused by a disturbance on the grid to which power is being supplied
Lightning-induced failure/suspension	System or component failure due to lightning strike
Environment-induced failure/suspension	Degraded system condition caused by environmental factors other than lightning (e.g., hail, wind, wildlife, etc.) or by array maintenance activities (e.g., grass or weed control)
Hardware application problem	Energy loss due to poor design for the application • Example: Unaccounted for building shading
Vandalism	System or component failure caused by vandalism (e.g., cracked modules from thrown rocks)
Unknown	The incident source is unknown and either does not fit into any categorization or is not categorized by the user
Hardware upgrade	A batch of identical components replaced with upgraded versions prior to failure • Example: all inverters replaced, new ac disconnects installed based on utility upgrade
Software upgrade	The system, in part or in whole, is offline in order for the manufacturer to install new software • Example: tracker controllers, monitoring systems
Planned maintenance	Scheduled maintenance (routine or otherwise) such as cleaning operations, hardware modification or replacement, tracker mechanical maintenance
Troubleshooting issue	A failure or suspension due to the troubleshooting process • Example: while changing a fan in an inverter, a capacitor is broken
System upgrade	A general upgrade to the system

	• Example: another PV array with inverter is added to an existing PV system
End of useful life failure	The failure cannot be repaired

2.2.3. PV System Performance

Table 6 provides a few of the main PV system performance parameters. Many of the PV system performance metrics that will be measured over the project's lifetime will depend on the system size and the degree of accuracy required by the original specification documents and service contracts. Some contracts may track performance separately with the component availability, some may track performance inside the equation for determining availability and call it "energy availability." IEC 61724 provides a good outline of PV system performance parameters that are used internationally. This standard is currently undergoing a revision to include two parts. The first is "Photovoltaic System Performance," and the second is an "Energy Evaluation Method." Much of the initial framework for this revision is described by Kurtz et al. (2013).

Table 6. PV System Performance Parameters

Description of Data Need	Notes
Measured site solar insolation	Reference cell, pyranometer, etc. See IEC 61724.
Estimated site solar insolation	From performance model or forecast. See IEC 61724.
Weather data	From site and regional. See IEC 61724.
dc kWh production	Can be captured at each inverter, or central inverter depending on configuration.
ac kWh production	Recorded from a utility grade meter.
Other test data	Qualification testing, accelerated aging, lab, etc.
Energy Yields	See IEC 61724.
Yield Losses	See IEC 61724.
Performance Ratio	See IEC 61724.
Efficiencies (array, BOS and plant)	See IEC 61724.
Model used for developing lifetime performance estimates	Can be used to compare PV performance estimates using predicted, expected and measured energy.
Degradation rates of components	Known or modeled in % power loss/year.

SNL organized the PV Performance Modeling Collaborative (PVPMC),[10] which aims to improve upon PV performance models in terms of accuracy, definitions and transparency. Many of the resources available from the PVPMC page can help determine what initial, intermediate, or calculated parameters are necessary for tracking the performance of a PV system over its useful lifetime and appropriately tying that to event information as discussed in an "information model" concept discussed further in Section 4.2.3.

[10] https://pvpmc.sandia.gov/

2.2.4. O&M Related Costs

The cost metrics shown below in Table 7 are an example of the high level costs that can be captured and tied to specific events in the PVROM database. NREL is currently working on a pro forma O&M model, discussed in more detail in Section 4.1.2 that can be used for commercial, residential, and ground-mount PV systems (Walker at al., in preparation). A large list of different scheduled and corrective maintenance schedules is available, as well as the ability to include different labor and component costs. For PVROM, any cost metric desired can be included in the analysis.

Table 7. O&M Cost Metrics

Description of Data Need	Notes
Budgeted O&M cost	From original agreement with EPC or O&M provider.
O&M service contract	Contingencies that lay out who pays for what and who is responsible for liquidated damages and what is covered under force majeure events.
Installed cost	The overall installed cost pre and post incentive.
Component and activity cost estimates	Estimates of the replacement cost of components, and labor hours to perform either preventative or reactive maintenance.
Labor rates	Different employee classes including electricians, IT support, engineering, and technicians, for example.
Component and activity cost - actual	Actual cost of component replacement, and labor hours to perform either preventative or reactive maintenance.
NPV of components (lifetime)	The average cost per year as well as lifetime and percent of total (present value minus cost).
Lost revenue	Any lost revenue associated with system downtime (availability guarantee) or performance guarantee. Contractual terms will dictate who is liable for liquidated damages.
Warranty items	Which items are covered under warranty for service and replacement. Any associated costs should be tracked if not covered by the warranty (labor, shipping, etc.).
Insurance policy	Which events insurance will cover and up to what amount, including annual policy costs.

2.3. PRVOM Database Outputs and Analytical Capabilities

It is possible, at any time, to extract incident data from XFRACAS™ for analysis. This is the chief purpose of the PVROM process. Typical data processing reviews the incidents for any systematic issues that may be present or suggest possible single root-causes. Analysis of failure and maintenance data can assist in this effort. Calculation of failure frequencies and restoration times per component can help construct metrics which indicate whether the system may be improving or declining in overall performance. System and component level metrics will give a system owner or operator a holistic view of the system health with regards to reliability and maintainability. The primary goal of review and analysis is to ultimately improve both of these attributes through informed design and management decisions.

PVROM functions as a database tool by which pertinent information can be harvested for analysis proposes. The following are readily available as outputs of PVROM:

- *Incident Frequency* – the rate of occurrence for any particular outage events for systems or components
- *Repair Duration* – the difference between event service response date/time and service completion date/time, to nearest hour (reliability metric)
- *Restored to Duty Date/Time* – the date/time that the system, subsystem, or component is once again performing its intended function following failure or an out-of-service event
- *Down Time* – the difference between event occurrence date/time (date/time failed or out of service [OOS]) and restored to duty date/time, in hours (availability metric)
- *Service Down Time* – the difference between event occurrence date/time (date/time failed or OOS) and service completed date/time, in hours (availability metric)

2.3.1. Analytical Capabilities

PVROM has reporting capabilities for tracking and gathering the statuses of incidents from their opening to their closure. Data can be downloaded instantaneously from PVROM to allow for immediate processing and subsequent analysis. The PVROM process encompasses three broad areas of analysis:

1. Producing system-level and component metrics that assists in understanding the broad health and status of a system. This includes being able to review individual incident reports to find possible systematic issues that need to be addressed.

2. Constructing time-to-failure and time-to-restore metrics to quantify both current and future (predictive) system reliability and maintainability. The metrics can be further used to construct models to predict ongoing system performance such as availability and trending (reliability growth). These models can also be used for the construction and analysis of others that account for additional performance aspects of a system.

3. Comparing diverse systems: diversity in environment, geographic location, implemented technology, and maintenance policies. The effects of all of these variables are usually only apparent when enough evidence has been gathered to analyze differences. It is difficult to determine the impact and cost trade-offs of preventative maintenance on a system that for which preventative maintenance has always been employed; therefore contrasting different partner implementations can provide insight into these trade-offs.

2.4. Example Analysis Results

This section presents the type of analysis that can be performed via the PVROM database. Supplemental information that describes setting up BOMs (Hamman, 2014) and early analysis results collected during the PVROM project’s first year of study (EPRI, 2013) may help provide the reader with additional context. The below illustrative results are intended to offer greater insight into the overall reliability state of a PV plant (decreasing, steady, improving), and how those states are expressed through overall system performance and costs incurred over time.

Following is an example Table of Contents for a quarterly O&M report that can be populated via analysis derived from the PVROM tool.

1. Introduction
    a. Purpose of Report
    b. Scope of Report
    c. Reference Documentation (as needed)
2. Quarterly Overview
    a. Number of Incidents Opened and Closed
    b. Notable Incidents and Broader Partner Issues
3. System Metrics
    a. Quarterly Partner System Metrics
    b. Quarterly Partner Aggregate System Metrics
4. Component Metrics
    a. Quarterly Partner Component Metrics
    b. Quarterly Partner Aggregate Component Metrics
5. Conclusions and Recommendations

The metrics proposed for a standardized report are intended to give a high level understanding of system and component behavior from reliability and maintainability perspectives. Each report should reflect on *system* and *component* metrics—system data should reflect a window of the previous year of data, while component metrics should reflect the previous three months. Although the below data shown for these metrics are not representative of an actual system, they are meant to convey how potential data gathered from partners can be used to discern system and component health. Table 8 describes the set of metrics that should appear in a standardized PV O&M report.

Table 8. Quarterly O&M Report Terms and Descriptions

System Metric	Description
Energy Loss (see Figure 3)	The estimated energy loss is based on maintenance actions (corrective or preventative). It includes both the absolute energy loss in kilowatt-hours and ratio of the PV system yield to the reference yield (Performance Ratio) that could have been generated if maintenance activity was not required (given no faults/failures or no preventative maintenance).
Availability (see Figure 4)	The fraction of a given operating period in which a component is performing its intended services within the design specification. It would only include the time that the system was expected to be available to produce energy (e.g. daylight), only account for maintenance actions that cause loss of power to the system, and. be based on an agreed-to threshold of service required of the system. If the system fell below the threshold it would be considered "unavailable:" if it stayed at or above the threshold it would be considered "available." Partial production is addressed by Hill et al., (in preparation).

System Metric	Description
Total System Labor Hours (see Figure 5)	Total labor costs per month segmented by three labor types: unskilled, skilled, and professional based exclusively on maintenance activities.
Logistical Downtime (see Figure 6)	The amount of downtime that excludes active (hands-on) repair of a system. This includes accounting for travel time of staff, ordering parts, judicious scheduling of resources or deliberate wait-time based on external constraints, retrieving spare equipment, etc.
Component Contribution to System Energy Loss (see Figure 7)	The percentage of the total energy loss over the previous quarter per system component. This is the bottom-line impact of component maintenance action on system productivity.
Component Maintenance Actions (see Figure 8)	The total number of maintenance actions per component over the previous quarter.
Total Component Labor Hours (see Figure 9)	Total labor costs per component over the previous quarter. Laborers should be segmented by at least three labor types: unskilled, skilled, and professional based exclusively on maintenance activities.
Total Active Repair Time per Component (see Figure 10 and Figure 11)	The total active "hands-on" repair time for each component over the previous quarter.
Component Reliability/Maintainability Metric (see Table 9)	For each system component a list of the following metrics over the total (cumulative) life of the component in the system: • Mean Time Between Maintenance Actions (MTBM) includes all incidents that required maintenance on a component regardless of whether there was a precipitating failure or not. • Mean Time Between Failures (MTBF) includes all incidents that required maintenance on a component and lead to the repair or replacement of a component because of failure. • Average Active Repair Time. • Total Energy Lost (kWh). • Total Labor Hours. • Total System Downtime – the total downtime to the system caused by the outage of the component. • Failure Time Percentiles – show the 10^{th}, 50^{th} (median), and 90^{th} percentiles of the observed failure times (those maintenance actions required repair or replace of a component). • Repair Time Percentiles – show the 10^{th}, 50^{th} (median), and 90^{th} percentiles of the observed repair times to a component.

2.4.1. System Level Metrics

2.4.1.1. Lost Power Production Due to Maintenance Actions

Component outages, whether planned or unplanned, impact the system's ability to produce energy. Figure 3 illustrates how energy production can be impacted by varying levels of system reliability and maintainability (and influenced by preventative maintenance and corrective maintenance decision making).

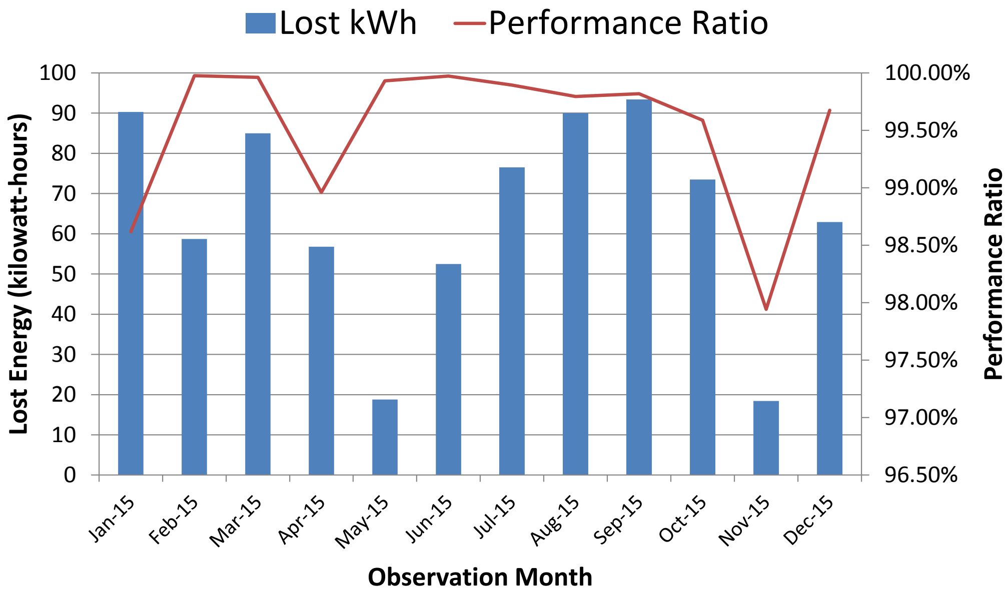

Figure 3. Lost Energy and Performance Ratio – Example

The Lost Energy and Performance Ratio metrics can be considered the "bottom-line" metrics of the entire system. They directly answer the question of how reliability and maintainability impact the primary function of the system, which is energy production.

2.4.1.2. System Availability

System availability tends to be a more complex measure because it is dependent on the owner's definition of availability with regards to system design. Generally, availability is defined as the fraction of a given operating period in which a component is performing its intended services within the design specification. It has also been defined as the percentage of time that the system produces power over a prescribed threshold or based on the number of inverter strings producing power. What the metric represents needs to be discovered and negotiated on a system by system basis. However, it is assumed that availability will be a ratio of total time that a system is considered to be available over the period of interest. Therefore availability will always be a number between zero and one (Hill at al., in preparation).

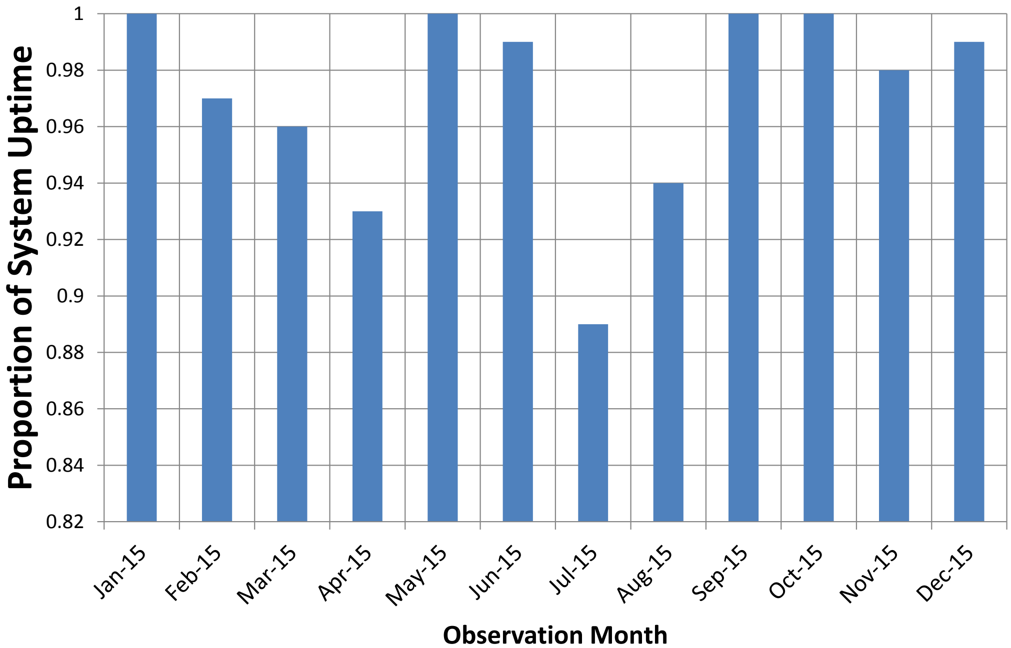

Figure 4. System Availability – Example

Assumptions, constraints, and ground-rules of the system availability calculation need to be meticulously documented to give the proper context and understanding. System availability is a metric that can be widely interpreted and may have several caveats depending on contracts that the system owner may have with customers.

2.4.1.3. Total System Labor Hours

The total system labor hours is primarily a financial metric relating the impact of maintenance actions performed by a responsible work force on system operations. This monthly metric shown over the previous twelve months is typically segmented into three types of labor:

- Unskilled labor that requires a limited amount of training or procedures to complete. Typically those titled as "technician" would be considered unskilled labor and would perhaps be responsible for washing panels or performing vegetation control.
- Skilled labor that requires advanced training and usually certification to perform.
- Professional labor that requires advanced training or certification to maintain or replace certain electrical components; responsibilities may also include activities such as design and project management.

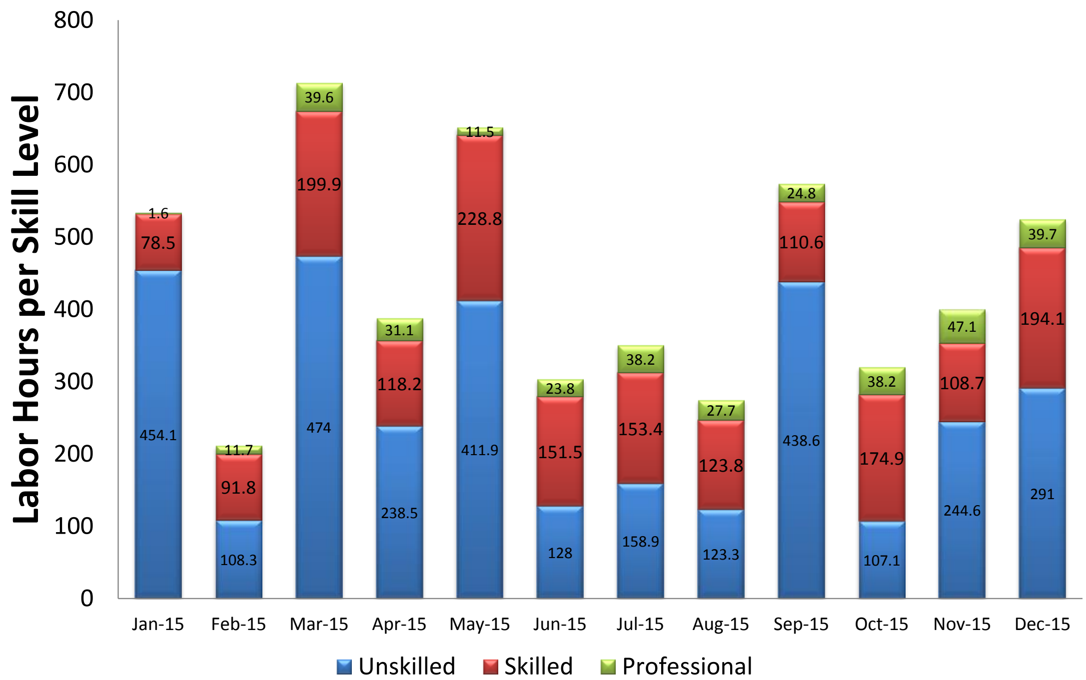

Figure 5. System Labor Hours per Month – Example

Understanding system labor costs is complementary to understanding system performance in terms of energy loss due to maintenance activities and system availability. It answers the question of how much continuous effort is required to maintain system performance at an expected level. If a project manager interprets that too much labor is being expended or too much of a certain labor type relative to observed performance is being utilized, then that will likely lead to appropriate scrutiny of the reliability and maintainability of the system. Among example questions that could be elicited:

- Are high-maintenance components failing more than expected?
- Are maintenance activities taking longer than expected? Perhaps removal and replacement of equipment is not happening at the right level in the system. Perhaps work-instructions are unclear or incomplete.
- Are the right skill-level personnel being used for the right type of maintenance activities appropriate for them? In some cases, a journeyman electrician or engineer may be performing simple replacement of consumables that would be appropriate for an unskilled worker.
- Is there time wasted in personnel tracking down spares or other logistical tasks?

System level metrics do not directly answer what the root causes of performance problems may be; they instead generate the right questions for tracking down and eliminating the root-cause of system inefficiencies.

2.4.1.4. Logistical Downtime

The downtime experienced by system components can be caused by unplanned or planned events. Unplanned events include component failures or outages caused by external factors such as grid disturbances. Planned events usually only include preventative maintenance. For either case, maintenance actions require many steps to ensure that components become available for service. The steps are broadly categorized under active repair and logistical tasks.

Active repair includes the tasks that are required to isolate a component needing the repair (or preventative maintenance), repair or replace the component, test the component to ensure that the maintenance action was successful, and reintegrate the component into the system as a whole. Logistical tasks include the remaining activities to support corrective or preventative maintenance, such as acquisition of spare components or consumables, travel time of the maintenance crew, processing of paperwork, etc. Both active repair and logistical maintenance tasks contribute to the total downtime of individual components and hence the system as a whole.

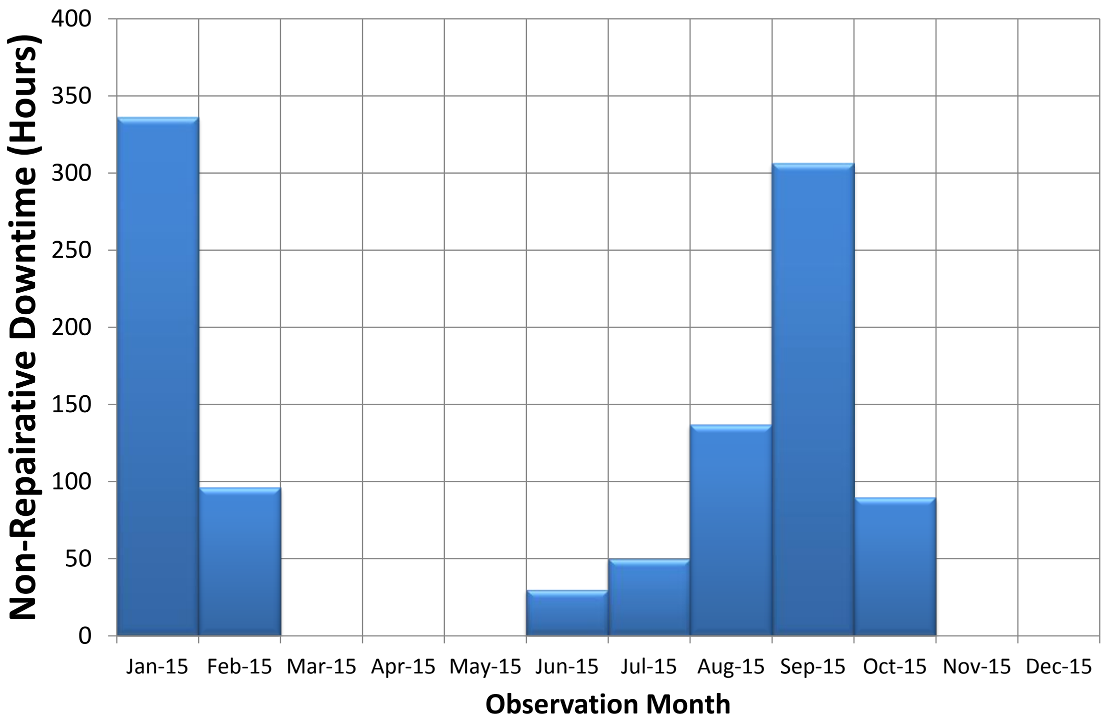

Figure 6. Logistical Downtime – Example

Understanding how much downtime is due to activities indirectly related to system maintenance provides the capability to identify areas of possible inefficiencies or inadequate planning. Long downtimes due to non-reparative actions could be indicative of a maintenance strategy that does not employ a holistic view of system maintenance. An example may be that a maintenance contractor visits the site each time an incident is reported. Perhaps it would be more efficient for the maintenance crew to only respond when a certain number of non-critical incidents reach a predetermined caution level, where that level would be set based on the perceived impact to system availability and performance. This would reduce the number of "truck rolls" and coordination that comes with each site response. Increased logistics time may also be an indication of insufficient on-site component spares thereby leading to additional time to acquire off-site spares or initiate just-in-time procurements.

2.4.2. Component Level Metrics

2.4.2.1. Component Contribution to System Energy Loss

Component reliability and maintainability ultimately affects system productivity. Whereas system metrics help understand the health of the system as a whole, components uncover the cause of the undesired system behavior. The component level metrics represent the impact of various component families (inverters, photovoltaic modules, transformers, etc.) as a whole. Most of the proceeding charts compare system components to each other, while Table 9 (Section 2.4.2.5) shows the absolute metrics of each component family over the life of a system, as captured in PVROM.

Figure 7 provides an overview of how each component family affects a system's performance with regards to its primary function of energy production. This metric should be analyzed in context of the system as a whole. The system project manager or systems engineer would discern whether or not a particular component was having a greater impact than its placement (i.e. its system interconnectivity) warrants in the system and how many and what type of other BOS equipment or photovoltaic modules are connected both upstream and downstream of that component. Figure 7 can also be looked at from an availability standpoint, if desired.

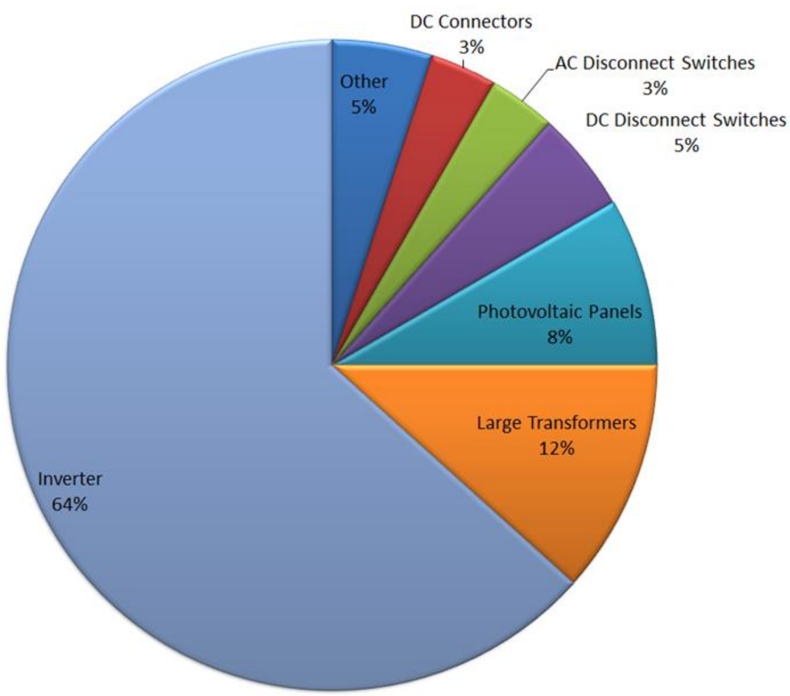

Figure 7. Component Contribution to System Energy Loss – Example

2.4.2.2. Component Maintenance Actions

What component failures (or preventative maintenance) impact the system the most with regards to energy production? For all the component families such as inverters, photovoltaic modules, and large transformers, the impact may be vastly different from system to system. This is not only due to failure rates and quantities in the system, but also because of the system configuration itself. A single loss of a photovoltaic module will likely not have any significant impact to a large system, though a loss of an inverter or a large transformer connecting the system to the grid would have a notable impact.

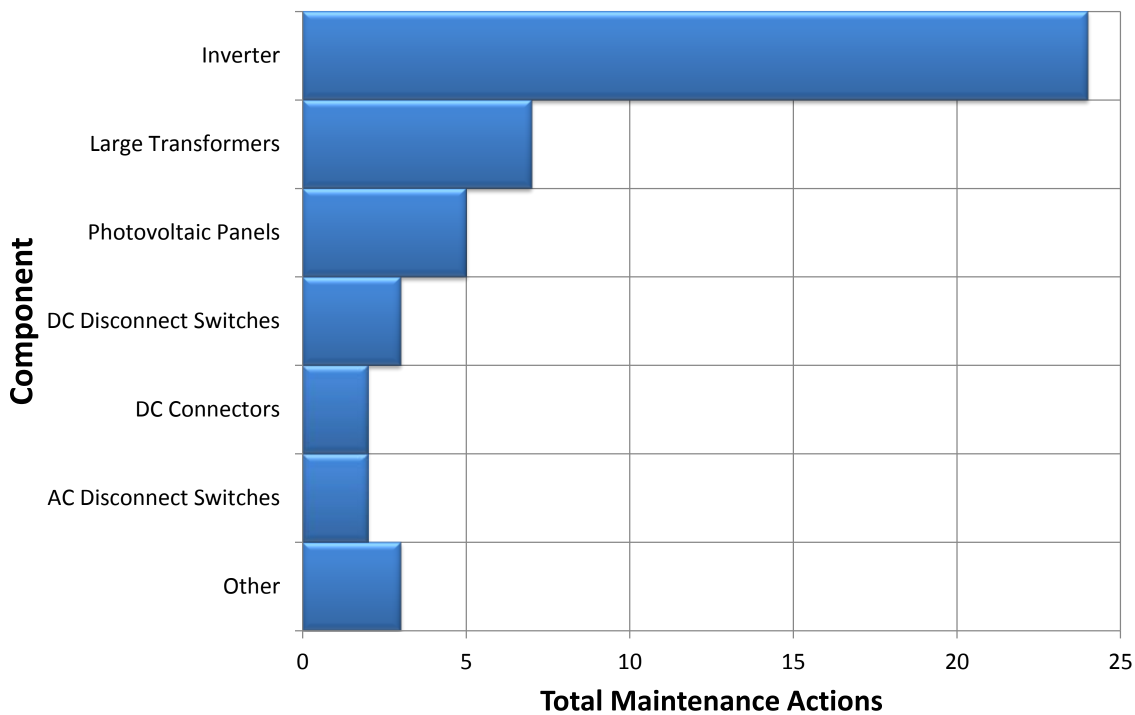

Figure 8. Maintenance Action Comparison per System Component – Example

The Pareto Chart in Figure 8 above lists top to bottom those plant components that, according to one system analyzed in PVROM, had the most maintenance actions. This metric helps project management quickly ascertain which components are requiring the most maintenance attention. Combined with Mean Time Between Failure (MTBF) data from component vendors, it can be determined whether or not components performed as expected. The systems engineer can also determine whether or not the information in Figure 8 is consistent with Figure 7 given their knowledge of system architecture. That is, does the amount of maintenance on a component correspond to the amount of downtime that is impacting the system? Inconsistencies would elicit further investigation.

2.4.2.3. Component Maintenance Labor Hours

Labor hours are broken out by each component and each labor skill type. Like component maintenance actions, this metric is shown in a Pareto Chart format (Figure 9 and Figure 10).

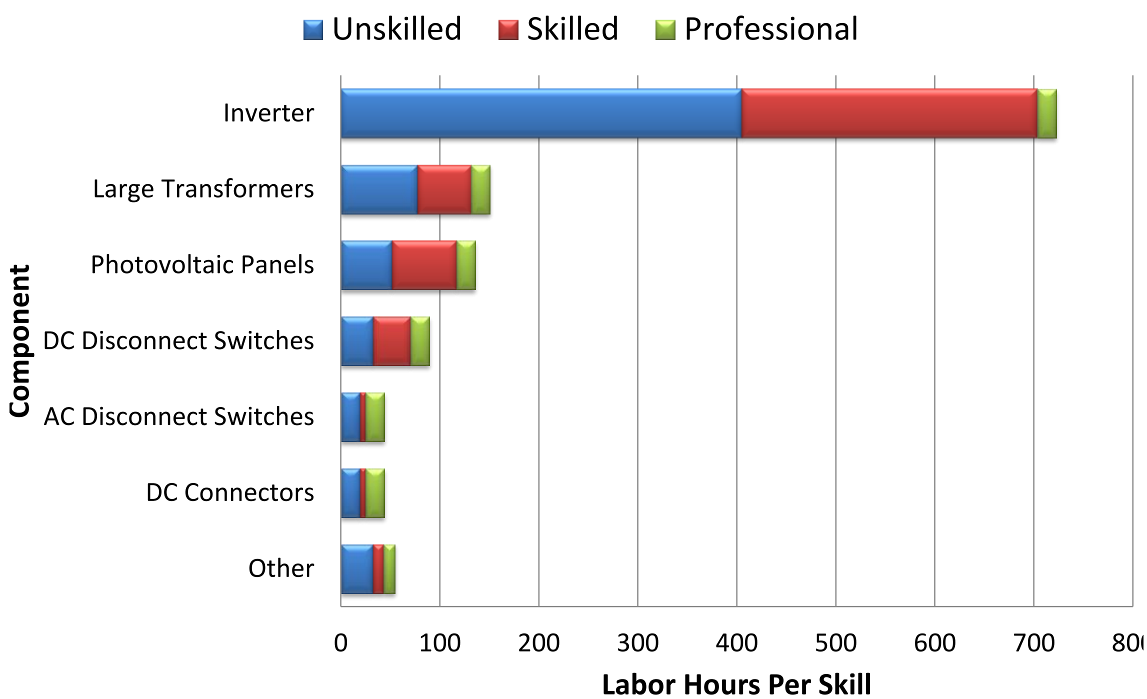

Figure 9. Component Maintenance Labor Hours – Example

The information shown in Figure 9 can help discern not only if the total amount of labor per component is consistent with the observed system uptime and number of incidents, but also if the right type of labor is being expended on component maintenance. Expectations would be that the more modular and maintainable a component, the lower amount of maintenance hours across all skills levels necessary; a shift in the percentage of labor to a lower skill level may also be warranted.

2.4.2.4. Component Repair Times

Total active (hands-on) repair time (Figure 10) for the previous three months shows the level of maintainability needed to support each system component.

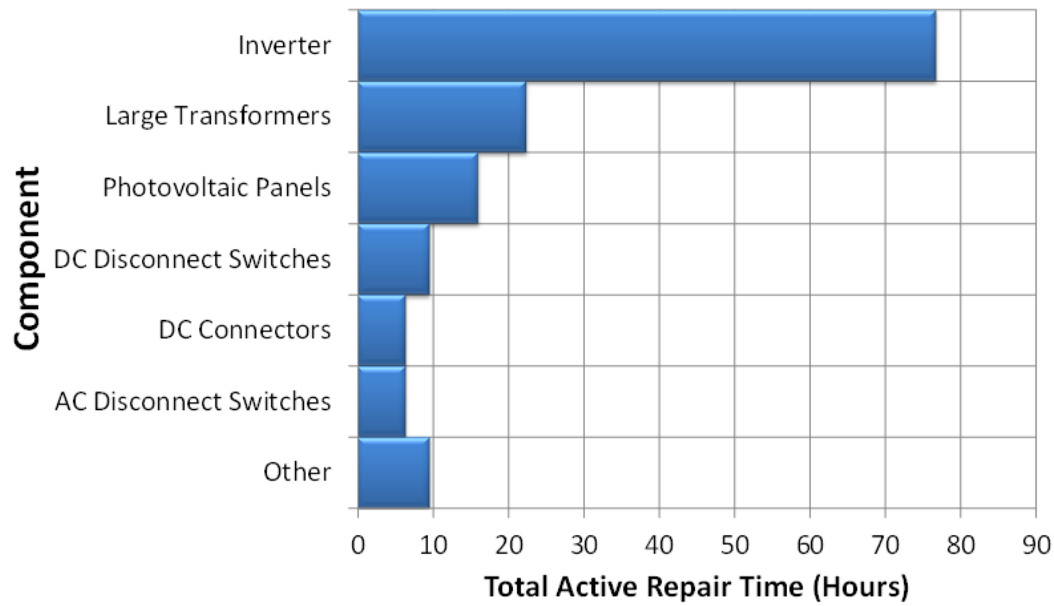

Figure 10. Component Total Repair Time – Example

This is another look at the individual component families' maintainability with respect to the system as a whole. The expectation is that Figure 9 (Component Labor Hours) will be consistent with Figure 10 results; if not, further investigation may be warranted. Individual repair times can also be charted to observe any potential trends in component maintainability. Figure 11 illustrates this by ordering the repair times by the sequence in which they occurred.

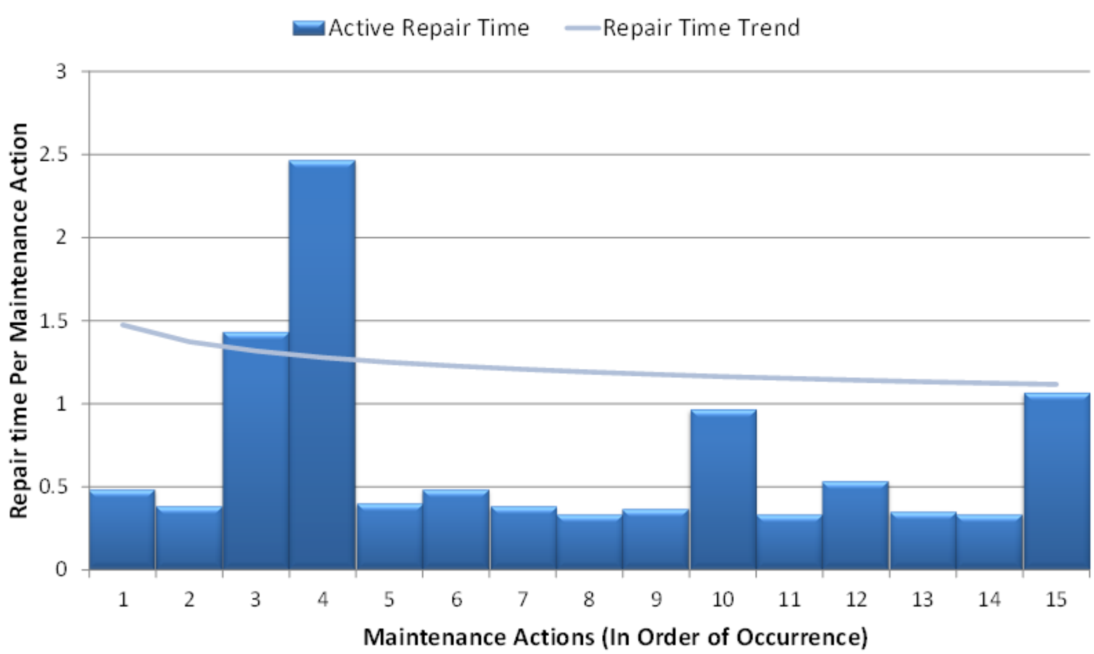

Figure 11. Active Repair Times per Maintenance Action for a Component (In Order of Occurrence) – Example

A trend, based on a simple regression model, gives a possible indication of how the expected repair time may decrease (or increase) as more maintenance actions occur. However, the main purpose of the trend is not prediction, but again to elicit questions about why repair times may be trending, and the essence of underlying causes of the maintenance actions themselves.

2.4.2.5. Overall Component Reliability and Maintainability Metrics

In some cases, it may be optimal to view all system components metrics in one chart or table so that quick comparisons can be made either between components or perhaps even with expectations set by vendors (such as MTBF predictions). Table 9 summarizes the typical component metrics of interest, such as the mean time between maintenance actions (MTBM) and mean repair time of the cumulative life of the system. Also, for purposes of seeing the extremities in the data, the tenth and ninetieth percentiles are given for both failure times and repair times to inform the system owner about the spread of these metrics.

Table 9. Component Metric Summary - Example

	Summary Maintenance Metrics				*Summary Availability Metrics*		*Failure Metrics in Percentile - Failure Time*			*Repair Metrics in Percentile – Repair Time*		
Component	**CUM. MTBM**	**CUM. MTBF**	**Avg. Active Repair Time**	**Total Comp. Downtime**	**Total Power Lost (kWh)**	**Total Comp. Downtime**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
Inverters	18,500	140,000	0.75	400	26	50	1,550	10,220	33,950	0.2	0.5	1.4
Photovoltaic Modules	54M	54M	4	10	4	0	5.7 E+06	3.7 E+07	1.2 E+08	0.4	2.8	9.2
Hydraulic Cylinders	10,560	10,560	4.5	0	80	0	6,500	12,680	16,000	3.6	4.4	5.2
Programmable Logic Controller	20.5 M	20.5 M	1.2	0	15	0	2,590	274,200	2,900,000	0.2	0.8	2.6
Data Acquisition system	14,112	21,168	0.3	0	1	0	1,490	9,780	32,490	N/A	N/A	N/A
DC Home Runs	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Fuses, ac and dc	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Utility Disconnect Switch	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Utility Power Meter	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Other components…	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E

With the exception of total power lost, all values are in hours.
N/E – no events
N/A – not enough data

2.4.3. Predictive Analysis

The reliability and maintainability data from PVROM can also be used to create empirical models to provide predictive capability. Natural questions that predictive analysis can answer include:

- What will be the system's lost power production (in kWh) over the next X number of months?
- What is the expected number of labor hours that will be expended over the next X number of months?
- What is the amount of spares that will be needed for component failures over the next X number of months?
- What would be the effectiveness of implementing preventative maintenance?

The predictive capability of these types of analyses greatly depends on the quantity of data available as well as its quality. Where data is lacking from PVROM, assumptions will have to be made and validated with the system owner or operator. Predictive analysis in PVROM is not generally done as part of a periodic report, but it is illustrated here to show what is possible.

2.4.3.1. System Power Efficiency Based on Maintenance Actions

One of the most important "bottom-line" metrics for a photovoltaic system is its ac power output. How maintenance actions impact power production is one of the chief measures captured by PVROM. The effect of maintenance actions on the long-term efficiency of the system can be predicted using modeling and simulation. The system model can account for wear-out failure modes in equipment or changes in maintenance policy. Figure 12 shows a possible output for such an analysis.

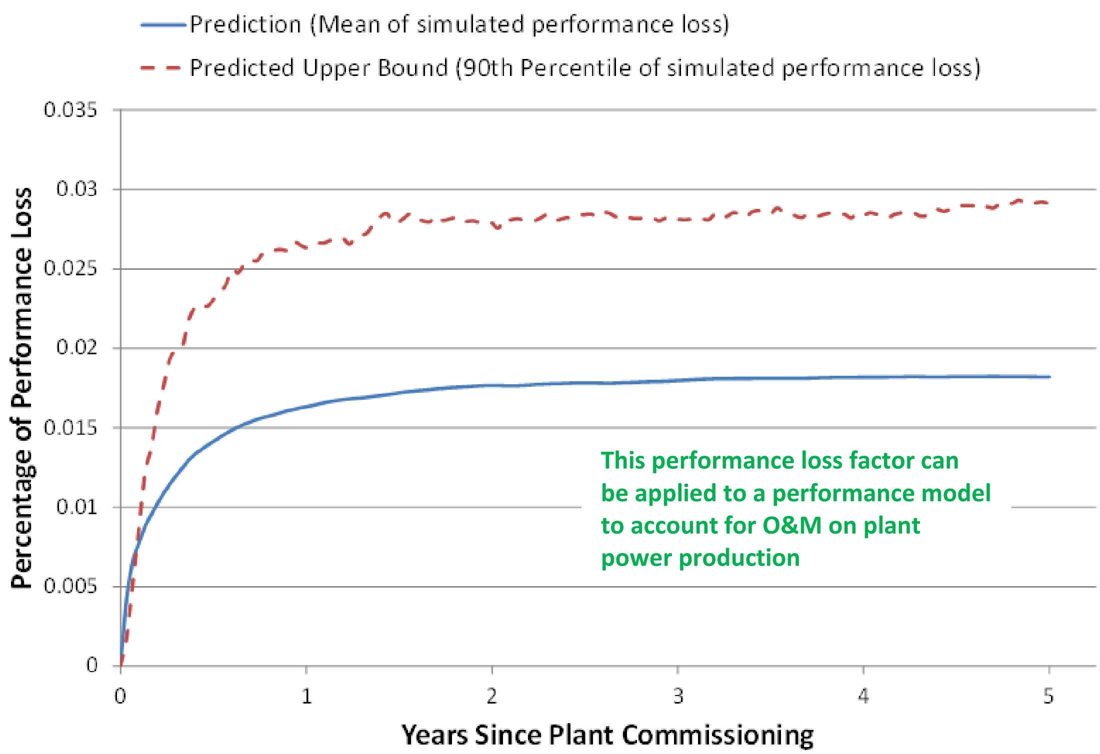

Figure 12. Prediction of "Yield Degradation" due to System Maintenance Outages

Predictive analysis allows for the construction of various "what-if" scenarios that hypothesize different system configurations, preventative maintenance policies, and even equipment replacement schedules to optimize the power production of a system. Figure 13 below shows a prediction of labor hours by skill category over a 6-month period.

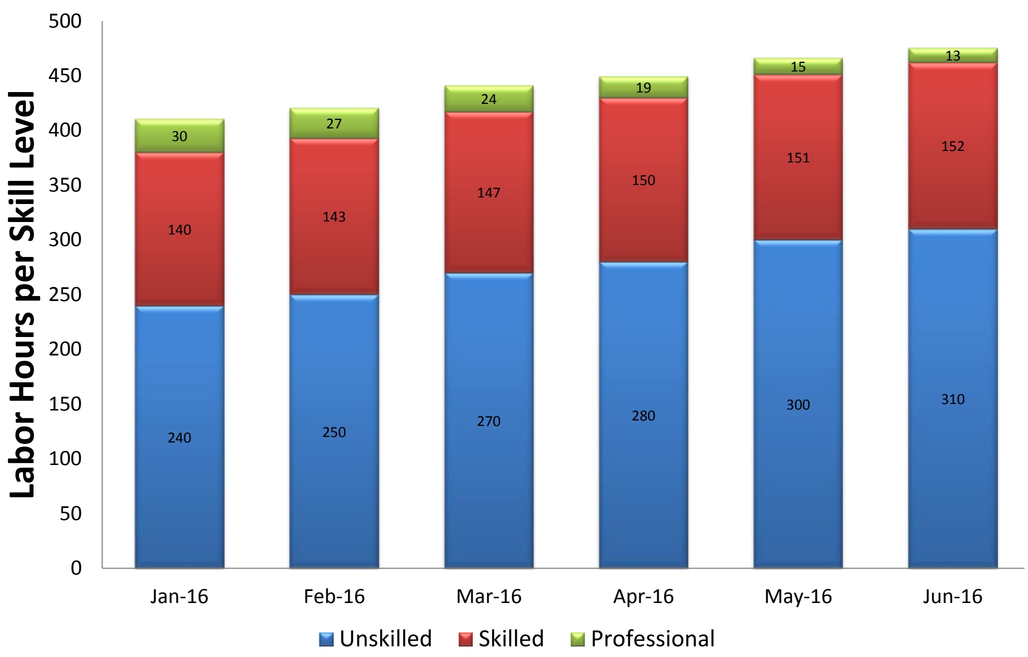

Figure 13. Predicted System Labor Hours

The opportunities that PVROM provides for predictive capabilities are twofold.

1. Using actual field data to build models based on actual failure modes as well as statistical data of failure and repair times to, in turn, construct scenarios to optimize plans for future outcomes.
2. Observing future data to ensure the accuracy of those models so that continued improvements can be made to both the system and the models themselves.

Examples include changing of maintenance policies, or early replacement of components that are beginning to enter the wear-out phase of life. Optimal inventory management of spares can lower the maintenance cost by decreasing parts on hand, freeing up space and cash flow. These benefits ultimately lower the operational cost of the PV plant.

2.3.3.2. Required Spares

Yearly financial planning for PV system maintenance may include corrective maintenance expenses to maintain a plant over the next year. Usually, spares will be required to be procured up front, before failure occurs, so that they can be deployed at a moment's notice. PVROM captures both component failure and replacement data needed to project the number of spares that will be required over any interval specified.

If component sparing is based on the average number of failures expected to occur over a time period, then sometimes there will be more spares than needed and sometimes not enough. However, it may be desired to have a certain confidence that a spare will be available when needed. It is assumed in this situation that an accessible spares pool would be maintained so as to avoid extended downtimes due to critical parts not being available for immediate procurement. Also, this approach lends itself to budget planning as spares could be purchased in bulk over a financial cycle.

It may be that a system operator would only accept a 10% risk of not having a critical component on-hand (or one that can be made rapidly available) when a failure occurs. If so, the number of spares required to achieve at least a 90% chance of having a spare when a failure occurs may be a more sensible type of metric. If trade-offs need to be made regarding the number of spares versus their cost, then a more detailed analysis could be conducted regarding the likelihood of having a spare available given a fixed number of spares purchased for the year.

The year-to-year component failure rates can change and this must be accounted for in any sparing analysis. If a particular component has a wear-out failure mode that is not evident in its first year of operation, it may show up in later years and increase the need for spares. Take for example a hydraulic cylinder used on a tracking system. It will not have a constant likelihood failure over time, but will be subject to wear-out failure modes later in its usage life. Using data from PVROM, components lifetime failure behavior can be modeled to predict future failures.

Table 10 shows the recommend number of hydraulic cylinders to be procured for a tracking system that has 35 in operation based on a 10% chance or less of running out of spares for each year. Note that in the first year the number of spares is much lower than the next four years. The component failure model predicts based on the fact that there is a wear-out failure mode in the component. However, the analysis also accounts for the fact that the failed component will be replaced with a good-as-new component.

Table 10. Sparing Recommendations for Hydraulic Cylinders

Year	Expected Number of Failures (in year)	Required Spares (for year)	Risk of Not Having a Spare
1	3.5	6	9.4%
2	18.7	23	9.4%
3	20.1	24	9.2%
4	18.4	22	9.1%
5	19.5	23	9.0%

This sparing analysis example demonstrates one method of controlling system availability by ensuring availability of parts and being able to predict certain system costs. A more practical sparing analysis approach would be to optimize total system costs with respect to system power production. An assignment of costs to maintenance crews (crew size, skill level, onsite response, etc.), initial costs of system components (purchase, installation), spares, and cost of repairs could all be considered in such an analysis. The PVROM tool, using Reliasoft BlockSim™ software, can conduct this kind of optimization analysis.

3. SUMMARY OF KEY FINDINGS

Information presented in this section serves as a status update to preliminary results outlined in EPRI (2013). Here, some of the metrics that have been analyzed with the first PVROM data partner are discussed at greater depth. (Note: The project relationship with the first PVROM data partner has recently been severed due to an ownership change.) In addition, the research plan for two of the three other existing PVROM data partners is presented. It is anticipated that the 2015 PVROM status report will include data findings derived from analysis of all existing PV systems under evaluation; some data is expected to cover 2-3 years of operational and maintenance information.

3.1. PVROM Data Partner Results

3.1.1. PV System Overview

Overall, SNL is analyzing data on 38 PV systems, one of which is in the northeast and the remainder in the desert southwest in California and Arizona. The smaller distributed generation PV systems in the desert southwest range from 3 kW_{dc} to 250 kW_{dc}. The larger utility-scale PV systems range from 1 MW_{dc} to 22 MW_{dc}. Most of the systems are fixed tilt, with the larger ones ground mounted, and the smaller distributed systems primarily roof mounted. Only two of the PV systems employ tracking technology.

Twelve different PV module manufacturers are represented that produce a range of different thin-film and crystalline silicon-based technologies. Some of the module manufacturers are no longer in business. Meanwhile, 6 different inverter manufacturers are represented across all of the PV systems.

3.1.2. Areas of Exploration

3.1.2.1. PV System with Tracking

The below analysis is based upon incident data—information covering plant operational deviations/failures, unplanned outage events, and associated mitigation activity—from one PVROM partner with two systems located in the desert Southwest. Both systems are similar in architecture (though one is slightly larger than the other in terms of total components). As a result of their comparable technologies and orientations, results and findings have been aggregated for the two arrays.

Table 11 lists the combined system components for the two installations, along with their total quantities. A summary of the number of maintenance actions, hardware repairs, and average downtime for the period January 1, 2012 to March 1, 2014 is also shown. Both systems have been operable for approximately 6 years, but the PVROM database has so far only captured their latest 26 months of system performance.

Table 11. System Components, Maintenance Actions, Repairs, and Average Repair Times

System Component	Abbreviation	Quantity	Maintenance Actions	Active Repairs	Avg. Active Repair Time (hrs)
AC Disconnect Switch	ADS	7	0	0	-
Combiner Box	CB	45	0	0	-
Data Acquisition System	DAS	2	4	3	0.3
Electric Motor	MOTOR	35	0	0	-
Hoses and Fittings	HOSE	35	0	0	-
HV Transformer	TXL	2	0	0	-
Hydraulic Cylinder	CYL	35	18	18	4.5
Hydraulic Pump	PUMP	35	1	0	-
Inverter	INV	7	8	0	1.5
Control Power Supply	CPS	7	1	1	4
Control Fan	FAN	7	1	0	1.3
Inverter Control Board	CRTLBRD	7	4	2	1.8
Inverter Control Software	CRTLSW	7	1	1	0.6
Matrix	MAT	14	4	4	1.4
LV Transformer	TXS	7	0	0	-
Misc. Electrical Devices, Cables, Connectors	ECON	2	1	1	4
Programmable Logic Controller	PLC	35	10	8	1.1
PV String	STRING	540	0	0	-
PV Module	MOD	8100	1	1	4
Solenoid	SOL	35	0	0	-
Tank	TANK	35	0	0	-
Utility Disconnect Switch	UDS	2	0	0	-
Valve Stack	VALVE	35	0	0	-
Variable Frequency Drive	VFD	35	0	0	-

Note: Evaluation of these two systems has ceased because system asset maintenance responsibilities have been transferred to another non-PVROM partner vendor. Incident tracking was halted in February 2014 and there will be no further capturing of current or historical data.

Since the previous report (EPRI, 2013), six new incidents were opened and a total of 11 incidents closed; this includes the five that were in an open status at last report. Therefore, all incidents have been closed; corrective actions have either been completed, no trouble has been found, or insufficient data has presented itself in order to identify an immediate root cause of the incident.

No components were noted to have increased failure rates since the last report. In fact, one of the "watch" components, the hydraulic cylinders (CYL), had additional failures, but fell below the expected number of failures given its previous performance from January 2012 to August 2013. The cylinders still experienced the same failure mode, leaking oil, which did not lead to immediate system degradation. The last failure of a cylinder was identified on January 22, 2014 when the predictive model expected approximately 24 failures to have occurred. However, only 18 failures were recorded. This may be considered a reliability improvement because there was action taken by the system maintainer, based on last year's analysis, to replace incorrectly specified seals on all hydraulic cylinders which exacerbated leakage. The seals were replaced in early 2014 and these failures were likely the last few that still had the previous seal design.

Another component of concern since the previous analysis was the programmable logic controller (PLC) for the tracking systems. The PLCs had a decreasing failure rate and there was one more failure recorded. This additional failure did not contradict the predictive failure model for PLC and the single failure itself only required a reset of the PLC. All other failures recorded since November 2013 have been unremarkable, though it is notable that there were no additional inverter (INV) or photovoltaic module (PV) failures.

As of this writing, data entry into PVROM for the two systems has ended. It is important that long term observation of systems continue when possible so as to track degradation of system components through use wear-out and environmental exposure. However, as ownership and O&M providers change, continued data collection becomes constrained.

3.1.2.2. Distributed PV Systems

An additional partner joined PVROM in 2014 contributing data from 30 distributed systems ranging from 11.4 kW_{dc} to 26.4 kWd_c nameplate capacity (see Table 12). The total line items refer to the number of items tracked in the BOM across all sites.

Table 12. Details for Distributed PV System Data Partner

Distributed PV Systems – Desert SW	
Number of Sites	30
Total Nameplate Power (MW)	0.45
Total Modules	2,017
Total Inverters	33
Total Line Items	3,041
Total Incidences	9
Observation Time (months)	6

Using the PVROM process, the contributing partner is recording the maintenance activity of the 30 disparate systems to find possible commonality in failures and root-causes. Also, given that each site is composed of different system configurations (flat and pitched rooftop, different inverters, modules and racking systems), the maintenance policies and actions can vary greatly. This partner is using PVROM to track both preventative and reactive maintenance strategies to primarily determine how differences affect overall safety and system reliability. The partner is also exploring how unifying maintenance plans may lead to an overall reliability improvement.

Since June 2014, two photovoltaic module failures were recorded and preventative maintenance checks were conducted on five systems. Future comparisons will be made on similar components in systems that have preventative maintenance and those that do not.

Over the next year this data partner plans to enter historic data into PVROM using maintenance checklists that were used before they started using PVROM; the partner will also continue to track labor hours related to maintenance activities.

3.1.2.3. Utility Scale PV Systems

Another partner joined the PVROM process this past year with 6 PV systems that total 34 MW. These systems range between 1 MW_{dc} and 22 MW_{dc} in nameplate capacity (see Table 13). A unique feature about this data partner is the level of detail that hardware subcomponents are being tracked. For example, in the case of one system, there are 44 subcomponents being tracked per inverter.

Table 13. Details for Utility Scale PV System Data Partner

Utility Scale PV – Primarily Desert SW	
Number of Sites	6
Total Nameplate Power (MW)	34
Total Modules	452,022
Total Inverters	29
Total Line Items	468,782
Total Incidences	6
Observation Time (months)	4

The partner has a tool for tracking maintenance activities using a trouble ticket database. However, they realized they could expand this capability to track systems statistics, including MTBF and mean time to repair (MTTR), more efficiently with PVROM. The data partner is particularly interested in being able to project long-term sparing across the regional sites by using the actual field failure data provided by PVROM.

Over the next year, this partner plans to expand their use of PVROM to include more sites with promise of additional geographic diversity. Presently, they are tracking photovoltaic systems both on the east and west coasts of the continental United States, with a majority of the systems in the desert southwest.

3.2. Areas for Potential Future Investigation

With data collected from PVROM partners over this next year, SNL will begin to compile fault and failure statistics and convey associated lessons learned. This will include translating the fault and failure metrics into a PV performance model as well as conducting an embedded survey of different PV system owners and operators to better understand and document current O&M challenges.

3.2.1. Assessment of PV-RPM Model Improvements

The PV Reliability Performance Model was developed to fill a need for having an accurate representation of reliability impacts to PV system performance (Collins et al., 2010; Miller et al., 2012). This model can be considered part of the PVROM “process” as it takes the event information and translates it into predictive models that relate how the events will impact equipment availability. PV-RPM also ties in a performance model that can run many realizations to better understand the uncertainty over time from probabilistic fault and failure behavior. The original demonstration model can be downloaded and used on a PC,[11] though it has limited ability to change the PV system configuration and different failure modes. An overarching goal of the PV-RPM effort is to leverage the PVROM information and formulate a systematic understanding of which components and operational considerations have the largest impacts on improving system-wide availability, reliability, and O&M costs. It is anticipated that the PV-RPM model will be improved with scenario analysis capabilities that utilize more advanced financial analysis capabilities and current PV system configurations.

Table 14 presents an example of in which PVROM data was translated into parameters that were used in PV-RPM . The data below was associated with the proof-of-concept modeling effort using the PV system in Springerville.

Table 14. PVROM Restoration Distribution Parameters for PV-RPM

Component	Distribution	1st Model Parameter	2nd Model Parameter	Mean Downtime (Days)
AC Disconnect Switch	Weibull	$\beta = 0.344$	$\eta = 0.460$	**2.447**
DC Disconnect Switch	Weibull	$\beta = 0.275$	$\eta = 7.530$	**105.55**
Array Electrical Connections	Weibull	$\beta = 0.631$	$\eta = 3.581$	**5.060**
Inverter - Corrective and Preventative Maintenance	Weibull	$\beta = 0.291$	$\eta = 0.0476$	**0.505**
Inverter - Induced Outages	Lognormal	$\mu = -3.685$	$\sigma = 3.137$	**3.438**
Photovoltaic Modules	Weibull	$\beta = 0.637$	$\eta = 4.556$	**6.37**
480/34.5 kV Transformer	Weibull	$\beta = 0.356$	$\eta = 21.678$	**102.50**

Notes: β (Shape Parameter of Weibull Distribution), η (Characteristic Life of Weibull Distribution), μ (log-geometric mean of the Lognormal Distribution), σ (log-geometric standard deviation of the Lognormal Distribution). Model parameters based on time metric of **days**.

3.2.2. Current O&M Challenges

SNL and EPRI are jointly proposing to collaboratively work with PVROM partners and other industry participants to elicit structured and detailed O&M and reliability information, failure rates, restoration times, and in-house best practices. The goal of this effort is to develop a white paper detailing current O&M practices, challenges, costs, and reliability insights. It will prospectively be undertaken to control input from participants so that it can be compared against multiple sites and PV systems. The paper will provide both qualitative and quantitative information on the state-of-the-art facing the industry. For example, it will explore the type of

[11] http://energy.sandia.gov/energy/renewable-energy/solar-energy/photovoltaics/pv-systems-and-reliability/snl-pv-performance-model/#.VFsB3Usq8ZE

reliability issues facing new PV systems with high dc to ac ratios, how O&M activities will be impacted by overbuilt systems, and what activity results in the greatest anticipated and unanticipated cost.

4. STANDARDS AND BEST PRACTICES DEVELOPMENT

The rapid worldwide growth of PV systems is generating increasing need to develop consensus O&M standards, maintenance procedures, definitions, and analysis techniques to sustain the industry's health. Definition and industry adherence has the potential to spur more efficient and responsible market and industry expansion in several key ways:

- *Improved project economics* – Well-established O&M practices can reduce the level of uncertainty in project estimates surrounding reliability, performance, and maintenance requirements.

- *Better informed, more segmented O&M activity* – Utilities, owner-as-operators, and also third-party O&M service providers are among those who perform O&M. Each brings a unique approach to asset management. Technical standards can establish recognized and consistent approaches for handling PV asset management.

- *Increased predictability of O&M costs and requirements* – Standardized maintenance protocols can improve confidence among market participants by enabling greater insight into measured performance outcomes.

In this space, SNL is facilitating a working group that is investigating best practices that can address the reporting of faults and failures experienced by PV systems. At the intersection of a better understanding of how PV systems fail is the opportunity for improvements where system downtime is reduced and work can be completed more efficiently within a given O&M budget.

4.1. Overview and Objectives

SNL has taken a multi-faceted approach to achieving O&M best practice objectives, coordinating with other working groups and standards efforts to ensure that activities are complimentary and important gaps in O&M knowledge are recognized. Many of SNL's contributions draw from the PVROM process described in this report. For example, fault and failure details collected in the PVROM database have, where possible, been shared with the working groups to aid in general knowledge development.

4.1.1. SNL PV O&M Working Group

The SNL-led PV O&M working group started meeting in 2013 to address O&M issues surrounding "Definitions," "Best Practices," and "Design & Installation." Since its founding, participation has grown to include a large cross-section of the solar industry, including OEMs, O&M service providers, EPCs, independent engineers, Yieldcos, fully integrated PV system providers, government, and standards efforts representatives. This effort has also since evolved into one that is now focusing on four core areas:

1. O&M Gaps and Improvement Efforts
2. PV System Availability Definitions
3. Availability Information Modeling

4. Predictive and Preemptive Maintenance

One of the first efforts undertaken by the working group was to identify industry-perceived gaps in O&M activities and compile the results of the gaps analysis. Details on this effort are presented below in Section 4.2.1.

Working group ideas eventually coalesced into focusing on the “Availability” of a PV power plant. The term generally refers to the state of equipment and its ability to perform a certain function. For PV systems, this term is now showing up in contracts with multiple definitions that in some cases include the “performance” of the PV system (i.e., the amount of kWh produced) and in others focus on keeping the equipment operational. This situation is further elaborated upon in Section 4.2.2.

The type of information collected from PVROM is being used to help set up the structure for an Information Model that may inform an “Availability for Photovoltaic Power Plants” best practice or standard. There are many industry drivers for this, which are discussed in more detail in Section 4.2.3 below.

4.1.2. Coordinated Efforts

Among other initial efforts carried out by the SNL PV O&M working group was to get involved with the ASTM WK43549 – Installation Commissioning Operation and Maintenance Process (ICOMP) standard effort. According to the ASTM and the draft document available at the time of this writing, “This practice details the minimum requirements for installation, commissioning, operations and maintenance process’ to ensure safe and reliable power generation for the expected life of the photovoltaic power plant. Specifically dealing with commercial photovoltaic installations, this practice covers a broad spectrum of designs and applications and shall be focused on proper process’ to ensure quality.” Many of the efforts that SNL is undertaking to improve O&M best practices—especially those outlined as part of the PVROM project—as well as plant “availability” are referenced in the ASTM ICOMP draft standard.

SNL is also working with the NREL PV O&M Collaborative Working Group to populate PVROM fault and failure distribution information into their pro forma O&M cost model for residential and commercial PV systems (Walker at al., In Preparation). Over 120 different fault, failure, and “action” modes associated with preventative and corrective maintenance have been added to the model in 2014, providing users with the ability to define distributions, in part, based on knowledge of observed or anticipated component performance in the field. Additional information will be supplied to NREL in 2015 to better define the distributions as data becomes available from the PVROM data collection and analysis effort.

The SunSpec Alliance is also developing many data sharing and storage standards that aim to help provide relevant and timely information to different stakeholders associated with the operations and maintenance of PV systems. SNL is working closely with SunSpec, and credits the organization for facilitating many of the early discussions on O&M gaps analysis.

4.1.3. SNL and EPRI O&M Workshop

As part of an ongoing effort to promote knowledge share surrounding state-of-the-art O&M technologies, business strategies, and financial modeling approaches, SNL and EPRI co-hosted a second annual PV O&M workshop in early May at EPRI's headquarters in Palo Alto, CA.[12] A component of the multi-day PV Systems Symposium,[13] convened to explore a range of technical issues related to PV systems and technologies, the well-attended one-day meeting explored a range of topics including current and conceptual O&M approaches for improving plant performance and reducing the levelized cost of solar electricity, advances in component reliability, and data-driven strategies for performing economically efficient system upkeep.

The main motivations behind the workshop were to convene industry leaders to share lessons learned and new insights around O&M activities; explore areas where technology can reduce O&M costs, boost performance, improve reliability; discuss recent efforts around the role of standards for both operations and maintenance; evaluate the effects of component and system reliability on an aging PV Fleet to better quantify the associated risks; and scrutinize O&M cost estimates and practices. EPRI and SNL ultimately leveraged the workshop to help advance O&M practices for boosting PV system performance and reliability at reduced cost. In identifying ways to simplify O&M through system design, and make O&M activities more predictable cost effective, workshop stakeholders sought to inform system design, protocols, and standards development activities.

The day included a mix of presented materials, panel discussion, and broad audience participation. (Participants included utility staff, PV system developers, plant owners, integrators, independent engineers, model developers, inverter and inverter component manufacturers, researchers, O&M providers). Among the issues discussed:

O&M Market Perspectives – Contrasting perspectives provided by an independent engineer, utility O&M manager, and private O&M provider underscored the differences in priorities assigned to the O&M function. Also highlighted were the range in O&M practices employed and budget rationales.

Rethinking Inverter Reliability and PV System Design – Field testing research results conveyed attainable improvements to PV component reliability and system design through novel measurement and evaluation techniques. Specific topics explored how both inverters and modules work in different environments (geography, weather, shading, soiling, measurement techniques) and regulatory environments (advanced inverter functionality), the ability of PV modules and inverters to withstand higher voltages and dc to ac ratios, and using IV curves to assess reliability and new degradation pathways. In addition, new ideas were related surrounding the commissioning PV Systems with a more explicit O&M focus.

Advances in O&M – A range of innovative PV O&M practices was discussed, including the use of unmanned aerial vehicles (UAVs) and robotic solutions to perform PV O&M, the integration

[12] http://energy.sandia.gov/energy/renewable-energy/solar-energy/photovoltaics/pv-resources/workshops/2014-pv-systems-symposium-details/2014-om-and-reliability-workshop/

[13] http://energy.sandia.gov/energy/renewable-energy/solar-energy/photovoltaics/pv-resources/workshops/2014-pv-systems-symposium-details/

of SCADA into PV system O&M practices, and a novel approach to automating periodic diagnosis of PV plant health and scheduling planned maintenance.

From a System to a Systems Perspective – SNL research efforts to capture real-time field data and gain insights into PV system reliability were related, as was analysis of how both operational and maintenance activities affect performance and cost. Preliminary PVROM results were shared to illustrate how actual operational behavior may diverge from initial component quality and accelerated aging testing typically conducted ahead of plant construction to discern potential performance impacts.

PV O&M Roundtable – Workshop stakeholders participated in breakout sessions intended to identify O&M practices that can boost PV system performance, reduce PV system costs, and enhance overall reliability.

PV O&M Standards Development – Best practices and standards efforts that aim to fill the gaps for ensuring quality O&M activities were reviewed. Many relevant efforts have commenced in the past year and time was used to discuss coordination among the multiple groups and discuss gaps in knowledge/coverage.

Ultimately, the workshop helped to underscore the importance of O&M for ensuring optimal PV system performance, recognize both technical and procedural advances in the field, showcase and coordinate standards development efforts, and acknowledge existing challenges. A number of outstanding issues were identified that require greater industry focus and attention. Among the most pressing:

- There is an abiding failure to consider O&M at the project development stage. A majority of developers are motivated to inexpensively build a plant that meet's near term requirements, rather than incorporate design approaches that can better serve a plant's longevity
- There are an abundance of O&M practices employed based on the specific contexts of individual plants, ownership priorities and perspectives, as well as finance structures. A steep learning curve exists to more efficiently and consistently apply them.
- Opinions about O&M budget allocation and prioritization differ among the various stakeholders involved in a PV plants development and operation. These differing perspectives are guided by self-interest, and greater coordination is needed to harmonize stakeholder interests in a way that can result in more optimal plant performance outcomes.
- Greater public knowledge around accurate cost information is a major knowledge gap. There is a need to generate metrics that can convey to financial stakeholders the cost-benefit of mitigating operational risks over a PV system's lifetime.
- There is a need for standardized data collection and analysis practices.
- SCADA and data acquisition systems (DAS) should be evolved to better serve the O&M function.
- Greater insight is needed into the trends and effective approaches for mitigating premature inverter failures, component reliability issues, and unplanned extended outages encountered throughout varying years of a system's operation. There is a related need to

separate system performance from equipment performance (i.e., the impact of individual component reliability on system-wide reliability).

- A framework for understanding O&M standards and best practice protocols will be necessary to progress the solar industry development and robust health.

The aforementioned challenges will be explored as part of a planned follow on workshop that is tentatively scheduled for 2015. In addition, an update on the progress of standards development efforts will be shared, as will findings from future research surrounding O&M costs.

For more information about the PV Systems Symposium (including the PV O&M Workshop), and to gain access to presented materials, please go to: http://energy.sandia.gov/energy/renewable-energy/solar-energy/photovoltaics/pv-resources/workshops/2014-pv-systems-symposium-details/#.VFuliGPYv6Q.

4.2. Status of Efforts

4.2.1. O&M Gaps Analysis Process and Results

SNL, working with High Performance PV and SunSpec, conducted a series of meetings in 2014 to document and review an O&M gaps analysis. This effort kicked off in March 2014 at a SolarPlaza O&M conference held in San Francisco, CA. The SNL-led O&M working group subsequently participated in numerous phone and web-based meetings. Notes from the meetings were compiled and reviewed by industry experts before a formal document was published as a white paper describing the many existing gaps identified.

The paper discusses areas where O&M standards and best practices can be improved. Those that were highlighted in the conclusions section are presented below with a short description. More detail can be found in the paper by Klise et al. (2014).

- **Homologized Standards** – Ensure that international standards can be accepted for use in the U.S., such as those developed by the IEC.
- **O&M Practitioner** – As more PV systems will need maintenance, there may be a need for certifying O&M practitioners. Voluntary certification is available for installers, however the skills may not necessarily transfer over, especially depending on the job task and electrical hazards involved with different types and sizes of PV systems.
- **PV System Specification** – There is a need for O&M to be prominent in the system/plant specification document, to ensure existing standards and best practices are adhered to throughout its lifecycle.
- **Consistency for the Insurance Industry** – Having information on how PV systems perform and are expected to perform will help allocate and underwrite risk. Industry operations and maintenance data will need to be collected and shared widely to better understand how the assets are performing over time.

Many of the identified gap areas can be addressed by PVROM. The PVROM "process," as described in this report and those published previously, is a best practice for collecting, analyzing and reporting on the reliability of a PV system. This process needs to be widely disseminated so plant owners and operators can improve their overall system availability and long-term reliability. O&M practitioners need to be good at troubleshooting. As such, having a good understanding of fault and failure modes identified by PVROM can help guide preventative and corrective maintenance activities. PV system specification can be informed by learnings from fault and failure event analysis; the PVROM process can help weed out certain types of events through root cause analysis. This learning can, in turn, extend into new PV systems through the development of specifications that pay close attention to designs and configurations that may prove to be problematic. Lastly, PVROM data can help identify and allocate risks by providing a probabilistic representation of how items may wear out, fail, and/or need to be replaced. Budgets and risks can be more accurately developed when probabilities are better understood.

4.2.2. PV System Availability Definitions

Early on in the working group meetings, participants encouraged SNL to help lead an effort to better understand the "availability" issue. One of the challenges facing the industry is the mixing of availability and performance guarantees in existing O&M contracts. When the O&M service provider enters into a service contract, typically after the EPC steps aside, he must meet contract terms and conditions or else face charges from liquidated damages for lost production or availability under specific thresholds. Production is ultimately tied to the "availability" of the equipment at the site, and maintaining the equipment under contractual terms where warranty timeframes and force majeure are well understood can help reduce uncertainty between the parties—which typically include the plant owner, O&M service provider, OEM equipment warranty, EPC warranty, and insurance company.

Depending on the cause of the event, whether equipment- or weather-related, proper accounting of the downtime and who/what it is attributed to is necessary. SNL, along with the O&M working group, is developing a flowchart of "availability," separating it into three areas shown in Figure 14. It is intended to recognize the many factors that can impact the availability of the PV system as well as outline the party responsible for fixing identified problems.

A map will also be developed for others to use when defining "availability" as part of a contract that will account for most all events that could impact a PV system's availability. PVROM-derived data and definitions will be used to help build out the flow chart. Within one element of this chart is an Information Model that can separate the many dimensions of a PV system's availability "state," including the time for an externally caused event, the time impacts to the PV plant, and ultimately the energy inputs from that event. This Information Model is depicted in more detail in Section 4.2.3.

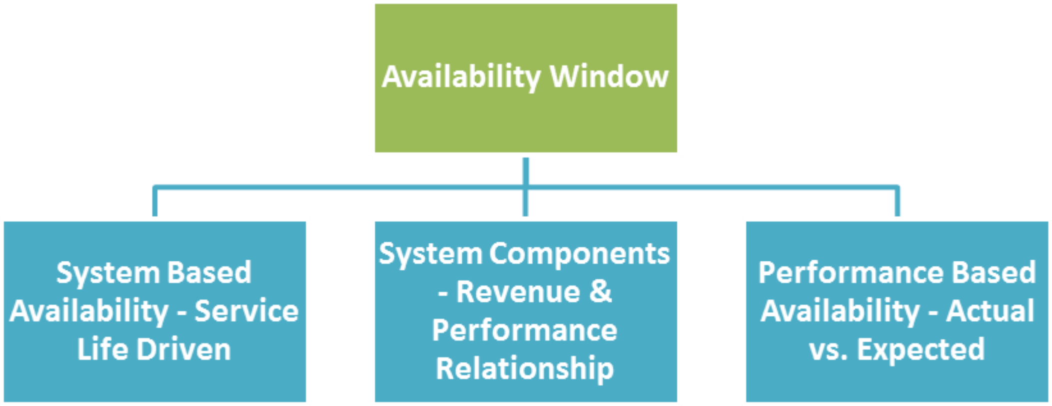

Figure 14. Draft PV Availability Definition – Relationship Map

4.2.3. Data Needs for Availability and O&M Reporting

Many of the challenges faced by the PV O&M industry are due to the many different types of ownership and O&M arrangements that are configured to take advantage of different incentives and tax benefits early on in a project. These arrangements govern the degree to which O&M is performed at different stages in a PV system's lifetime. Differing levels of service may potentially impact the overall availability of a PV system, which then affects the amount of energy produced and delivered. Having a consistent set of definitions will help when reporting system status and adherence to contract terms. It may also help with future regulatory frameworks that are not currently being mandated for certain PV system sizes and classes, but may become important if reporting requirements for NERC, such as the GADS database, are eventually required.

SNL is currently preparing a new work item proposal for a PV standard on availability. It will build on IEC-61400-26 technical specifications developed for wind turbine and wind plant availability, and as planned, will lead to an Information Model that will be used as an initial basis for defining generic PV system terms. The Information Model will also be used to recognize and distinguish environmental and operational constraints related to system and component availability, lifetime expectancy, repairs and criteria for determining maintenance intervals. In addition, it will define terminology for reporting PV generated electricity based on generating unit availability measurements. Availability measurements are concerned with the fractions of time a unit is capable of providing service, taking operational aspects into account. (Fractions of time indicate partial performance, a key factor to consider for a PV plant in estimates and accounting of production.) Environmental aspects are related to temperature and other weather conditions, applicable to the whole plant. The technical specification will define terminology, generic terms, and proposed algorithms for reporting performance indicators based on time and production or capacity terms for a PV power plant. Each category will be described in terms of how it can be detected, categorized, and related to other categories by defining transitions, which help to facilitate exchange of information on performance indicators. Age-related effects can also be accounted for by addressing degradation and derating, depending on whether such impacts are expected, or better than or worse than expected.

The specification shall include all functions up to the electrical interconnection agreed between the generation party and the distribution/transmission party. The work item will include considerations of how the technical specification shall be based on, harmonized, or appropriately deviate from the definitions and methods described in IEC/TS 61400-26 parts 1, 2, and 3.

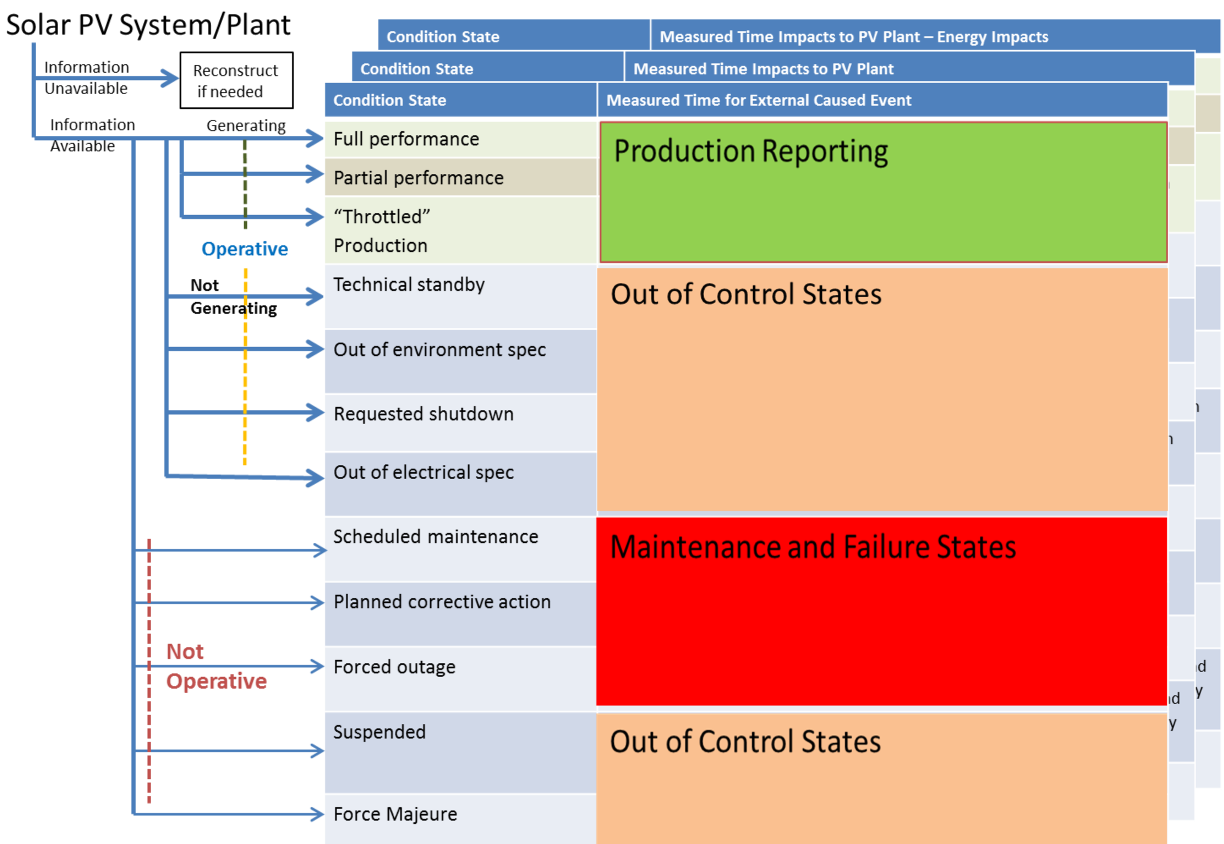

Figure 15. Availability Information Model – Conceptual Diagram

Based on the information model states presented in Figure 15, an accounting for time- and production-based tracking of performance can be created. The time in the various states of operation can be recorded. The production that corresponds to these states can also be measured and recorded. From this production basis, many accounting and performance comparisons can be accomplished. Outages will be correlated with the BOM impacted to identify what systems and components have been affected on a time and production basis. Deviations can be determined and assessed in terms of optimal performance, contractual demands, and allocations of production levels, and where excursions may excuse the obligation of the operator from delivery based on cause.

5. CONCLUSIONS

The PVROM process is designed to directly identify the metrics that improve overall PV production and performance, reduce events that act to reduce both plant energy and financial productivity, and provide a pathway for their mitigation. Its overarching aim is to provide data-driven PV system reliability and O&M findings that can be utilized to notify more strategic long-term thinking around solar plant operation and value. Specifically, PVROM intends to enable:

1. Identification of system component inadequacies and quantification of their associated system impacts.
2. Knowledge growth surrounding failure and repair time impacts that can be shared among PV industry operators and asset managers.
3. Shared O&M best practice insights among a broad spectrum of PV stakeholders, including those who develop, finance, perform due diligence, and/or underwrite projects.

SNL and EPRI continue to work at improving PV system reliability through the collection and analysis of event data, outreach to industry at annual workshops, as well as industry engagement to refine O&M gaps analysis and availability definitions.

New PV system configurations, such as string inverters, high dc to ac ratios, and increasing voltages will introduce new fault and failure modes that need to be understood to continually improve upon PV system reliability. Moreover, reduced incentive and system costs may place even tighter constraints on O&M budgets, necessitating optimal strategies for minimizing costs and maximizing plant uptime. Collecting reliability data will be necessary to meet forthcoming O&M challenges. However, it will be difficult, due to the many competing interests posed by PV system owners, operators, investors, and regulators. This should not deter current and potentially future data collection efforts, though. For example, as PV systems increase in size and play a larger role at meeting electricity demand around the U.S., it is anticipated that greater scrutiny on the reliability of those systems may occur, which could require additional monitoring and reporting of how these systems operate.

Despite the challenges in recruiting partners and getting data entered into PVROM, project work has helped data partners to understand how component events impact their overarching systems, as well as to document reliability improvements from early wear-out and design issues. Data partners expect to learn more about their systems to develop sparing and preventative maintenance strategies. With that information in hand, SNL will be able to populate event distributions in performance models, such as PV-RPM, and make the case for inclusion of reliability metrics in all performance modeling platforms.

As the industry matures and increases in size, all stakeholders will need to contribute to these and potentially other PV O&M research efforts by offering more component and system-level event information that can help developers and financiers better understand long-term project risks. PVROM work has helped to reveal a number of failure modes. It is now up to other system owners, operators, and OEMs to provide additional data to the PVROM initiative to help build the initiative’s data sample and, in turn, more accurately reflect the uncertainty and probabilistic nature of system events. As the PV system fleet ages and asset ownership changes hands, access to quality reliability information that can be easily understood will likely become increasingly valuable. Data that accurately represents the true condition of a PV system will ostensibly also increase demand for new systems, and keep risk-associated premiums to a minimum.

The PV industry stakeholders have expressed interest in adopting the PVROM process and utilizing it in their O&M platforms; discussions have been initiated in which consultants and asset managers would utilize these methods and platforms to better track O&M activities, including faults, failures, and preventative maintenance to improve the reliability of their fleets. In the coming year, SNL and EPRI plan to leverage knowledge gleaned from the PVROM project to suggest a series of O&M best practices that can in turn improve overall system quality both for existing and future PV plants.

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APPENDIX A: PVROM INFORMATION HANDOUT AND FREQUENTLY ASKED QUESTIONS

PV Reliability O&M Database (PVROM)

Descriptive Summary

BACKGROUND

Sandia National Laboratories and the Electric Power Research Institute (EPRI) have co-developed the Photovoltaic Reliability Operations and Maintenance (PVROM) database and a standardized data collection tool as a method to collect, analyze, and assess events and failures that occur in large (>100 kW) photovoltaic (PV) systems and plants. The PVROM tool is intended to enable data analysis exploring PV plant performance, reliability, and the economics associated with system maintenance and upkeep. It is, furthermore, aimed at using real world field data to examine trends that may inform optimal approaches to performing PV plant O&M.

PVROM partners, through their participation, gain access to a repository of solar data to benchmark system performance, identify root causes of system failures, and recognize cost-benefit tradeoffs in making value chain improvements. Ultimately, PVROM is meant to abet and accelerate the adoption of PV systems as a primary power generation source in the United States.

STAKEHOLDER ROLES

Sandia & EPRI

For ease of use and oversight, Sandia and EPRI operate and maintain the database as well as provide database access requirements to partners. This includes:

- Providing training materials and consultation to assist partners in entering and retrieving data, performing data analysis via existing PVROM algorithms, and completing other activities, as appropriate;
- Developing technical and administrative functionality embedded in PVROM (e.g., development of new algorithms, potentially adding database parameters to collect specific kinds of PV O&M information, etc.); and
- Supplying cyber security for the database.

Partners

PVROM partners—which encompass utilities, EPC/integrators, and third-party O&M providers—are responsible for initially entering and periodically updating field data information about their respective PV plants into the PVROM database. Activities include:

- Data entry detailing PV system characteristics (BOM, etc.) as well as planned and unplanned downtime incidents; and
- Use of PVROM functionality to perform data analyses, including comparative analyses.

BENEFITS

PVROM Partners receive multiple benefits of project participation, including:

- Data anonymity enforced by a Sandia-generated Non-Disclosure Agreement.
- Full database access to individual Partner-entered data.
- Database access to aggregated data entered by other Partners, normalized for use (contingent upon database sample size).
    - Analysis of aggregated data is intended to provide Partners with a way to benchmark their plant results with a larger sample while maintaining a level of anonymity.
- Increased recognition and understanding of PV availability versus reliability (and associated O&M options based on output).
- Benchmarking PV performance/reliability with that of other participants' that have input data into PVROM .
- Better understanding of system costs and cost-benefit of multiple O&M approaches based on various factors.
- Ability to, for example, provide plant performance/expectation to insurance companies at 5 year increments and better determine true plant value (and, in turn, renew insurance contracts via more favorable bank terms).
- Better understand the risk of possible future PV plant states (e.g., ID insurance products)

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PV Reliability O&M Database (PVROM)
Frequently Asked Questions

OVERVIEW

FAQ

1. What is the basis of the Sandia-EPRI PV Reliability O&M (PVROM) database architecture?

PVROM is run by a Web-based incident (failure) reporting, analysis, and corrective action system software package made by ReliaSoft and named XFRACAS (Failure Reporting, Analysis and Corrective Action System). A standard product, XFRACAS supports the acquisition, management and analysis of system quality and reliability data from multiple sources. The XFRACAS platform supports real-time and legacy failure/suspension (or non-failure events) data acquisition via real-time incident records created by an Incident Wizard and Incident Tracking Utility.

2. What data fields have thus far been set up in PVROM?

The following fields have been established in PVROM for Partners to input their data:

- *Incident Occurrence Date/Time;*
- *Bill of Material Part Number;*
- *Part Serial Number;*
- *Part Commissioning Date;*
- *Incident Description;*
- *Incident Category;*
- *Service Response Date/Time;*
- *Service Completion Date/Time; and*
- *Restoration to Duty Date/Time.*

Partners are welcome to recommend additional PVROM data fields to Sandia-EPRI for future implementation.

3. Is it mandatory that Partners use XFRACAS to input data into PVROM? Is data automation/export available?

For those Partners who already have a PV plant monitoring and data collection system in place, legacy data can be imported into PVROM via an Excel template. Note: bill of material (BOM) information is needed for each system input into PVROM, and Sandia-EPRI can input that information into PVROM for Partners. Legacy data is typically first exported, and then Partners can begin inputting real-time data (e.g., incidence).

4. Are Partners obligated to input a minimum number of PV facilities into PVROM?

No. Partners are free to, for example, engage in a test case and input data for a single site to evaluate the tradeoff in effort versus value. If Partners find participation to be of value, then they are encouraged to expand upon the number of PV systems they input into PVROM.

5. What quality standards will Partner-entered data be held to?

The data collection process is primarily a human input process as the data set includes O&M events, not SCADA data. Sandia-EPRI will provide training to each Partner and will be available to answer questions as needed. In addition, Sandia-EPRI will review the input of the BOM and incident data with the responsible management of each Partner. This is a qualitative way of ensuring what is entered into the PV-ROM is accurate and/or expected. Sandia-EPRI will also recommend preferred methods for calculating and reporting kWh lost for consistency across the database.

6. Is there a way to view and evaluate the quality of the data in PVROM before deciding to join the effort?

PVROM is a work-in-progress. Data evaluation prior to partnership is not currently available. However, Sandia-EPRI intend to work with early adopters to develop a quality index and training that helps ensure data integrity.

7. Bill of Materials (BOM) details of serial numbers for PV modules seems like a substantial effort. Is this necessary?

Including details down to the serial numbers for all primary components increases the usefulness of the data. A lower level of detailed monitoring can be used, but the results may not be helpful in the long run if module issues are batch-related, for example. Sandia-EPRI includes "shortcuts" for entering serialized information in the training process.

8. Can Sandia-EPRI provide a format for the bulk importing of performance data?
Yes. During a training session, templates will be provided to Partners along with direction on the level of information that needs to be included in the templates.

9. How are equipment categories defined and made reasonably consistent with varying plant designs?
As part of a training process, Sandia-EPRI provide a User's Guide that defines category and equipment fields. The guide also includes recommendations for categorizing equipment based on differing plant arrangements.

10. What is the overall level of effort necessary to properly input site data into PVROM?
Sandia-EPRI have a contract in place with PVROM's initial Partner to track the amount of time it takes to perform data upload/entry as well as the various issues encountered surrounding this task. An FAQ document will be made available towards end-2012 to convey this testimony.

11. How long does PVROM Partner training take?
Typically, PVROM training occurs at a Partner site and requires a full day—½ day for a user orientation, product overview, and questions; and ½ day to complete hands-on, scenario-based exercises.

12. Are all PVROM configuration and code changes done in-house?
Reliasoft's XFRACAS software product contains a level of flexibility for customization (e.g., the ability to add fields or set up email notifications to parties responsible for issues germane to a certain part of the system, such as reviewing incidence reports). Sandia-EPRI can make custom changes to the database in-house and personalize field parameters within each Partner entity. Sandia-EPRI encourage Partner feedback on additional fields to incorporate into PVROM in order to enable greater learning and overall value.

13. To what degree can proprietary Partner data be protected?
Sandia/EPRI sign Non-Disclosure Agreements (NDAs) with each provider of database content (typically plant owners) that clearly state the terms of data share. In general, these terms can be customized to satisfy Partner sensitivities and expectations. For example, terms can specify that Sandia-EPRI seek approval from Partners on all content intended to be included in both public and private reports prior to their publication. In addition, anonymity can be maintained by publishing findings based on an aggregate data level.

Moreover, XFRACAS, the platform upon which the PVROM database resides, provides a login ID and password to each Partner to ensure secure database access. XFRACAS resides on Sandia's restricted network server and Sandia-EPRI have access to each Partner "entity," or individual data input area, to perform comparative analysis at an aggregate level. No

Partners have access to other Partner data. XFRACAS source permissions ensure that source users can only access their own data.

14. Are failure analysis results publicly shared for particular PV plants?
All proprietary data will be protected under non-disclosure agreements. As such, failure analysis data for specific plants will only be shared publicly if the Partner agrees in writing to the publication of such data. Sandia-EPRI intend to publish non-manufacturer specific, non-plant specific, aggregated failure rate estimates based on a category of part, climate, module technology, etc. We plan to use aggregated data for public presentations to protect plant owners.

15. Given that the Bill of Materials is kept private, what value does it have for failure analysis? Will poor performing components across multiple owners' plants be shared?
The BOM and the system layout are necessary for data analysis to understand the statistics of what is failing and any location-dependent issues. Data analysis can be presented in aggregate formats to demonstrate general trends. If Sandia-EPRI observe an issue with a particular component across multiple sites and designs, we may approach the manufacturer directly and share the issue(s) we observe. We may also request that the Partners share the data themselves or in aggregate to bring awareness to the issue.

16. What reporting capabilities does PVROM offer?
XFRACAS supports incident record searches and report generation. In addition it supports export of data to ReliaSoft reliability life data analysis and reliability growth analysis software products, which allow Sandia-EPRI to perform predictive analyses, sensitivity studies, and optimized O&M strategies. Program Partners may use other XFRACAS capabilities as well (e.g., failure analysis, corrective action tracking, etc.)

17. At what frequency do Sandia-EPRI plan to publish reports based on PVROM data findings and analysis?
EPRI intends to publish a report exclusively for its members at the end of each calendar year for several years. The first report, scheduled for end-2012 publication, will provide introductory material that will set the stage for greater analysis and reporting in future years. Sandia will also produce one report per year that will be released into the public domain. As discussed above, no proprietary information will be released to the public without consent from Partners.

18. Is there a licensing fee associated with using PVROM?
Yes. Licensing costs are, however covered by Sandia-EPRI for the first five early adopter Partners. As of December 2012, two early adopters have signed-up for PVROM. Looking ahead, it is unclear whether these fees will be covered for future, non-early adopter Partners. It is a possibility that licensing fees for the first 10 Partner enrollees may be able to be covered. Also, it is unknown whether these fees can be covered in perpetuity.

19. What, to date, is the current number of PVROM Partners? What is the goal?
As of December 2012, two Partners have enrolled into the PVROM initiative, representing three systems that have a collective capacity of 11.5 MW. Sandia-EPRI would like to have a total of 10 Partners signed up by end- 2012, and over 25 by end-2013.

20. Is the methodology governing Sandia's PV Reliability and Performance Model available for review?
Yes, the methodology can be shared, and a demonstration is available on the Sandia website at: http://energy.sandia.gov/?page_id=6367. Sandia-EPRI welcome Partner feedback.

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